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CHARACTERIZATION OF SQUIB, MK 1 MOD 0:
THERMAL STACKING FROM RADAR-LIKE PULSES

15 SEPTEMBER 1961

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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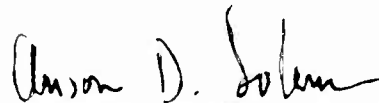
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CHARACTERIZATION OF SQUIB, MK 1 MOD 0:
Thermal Stacking from Radar-Like Pulses (U)

Prepared by:

L. D. Hampton & J. N. Ayres

Approved by:


Chief, Explosion Dynamics Division

ABSTRACT: The electro-thermal equations describing the heating and cooling of wire bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridgewire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for the varied input conditions and are all combined in a single nomograph. If the hot-spot theory is assumed the conditions for explosion can be deduced. For instance, for the Mk 1 Squib, a temperature rise of 500°C will result if the value of I^2R_W is 1,000 microjoules at a very low pulse repetition frequency (below 60 cps.) or is 100 microjoules at a frequency of 2,000 cps. This temperature rise would be expected to cause the squib to fire approximately 50% of the time.

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Explosions Research Department
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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15 September 1961

The work described in this report was undertaken as part of the program on the Hazards of Electromagnetic Radiation to Ordnance (HERO). It describes theoretical calculations which attempt to show how the temperature of a wire bridge EED is elevated by repeated radar pulses.

The work should be of interest to those working on the HERO program, to those using electro-explosive devices in ordnance applications, and to those actively designing, developing, and testing electro-explosive devices.

W. D. COLEMAN
Captain, USN
Commander

A handwritten signature in cursive script, appearing to read "C. J. Aronson".

C. J. ARONSON
By direction

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REFERENCES

- (1) L. A. Rosenthal, "Electro-Thermal Equations for Electro-Explosive Devices (U)", NavOrd Report 6684, 15 August 1959.
- (2) F. P. Bowden and A. D. Yoffe, "Initiation and Growth of Explosion in Liquids and Solids", Cambridge at the University press, 1952.
- (3) I. Kabik, L. A. Rosenthal, and A. D. Solem, "The Response of Electro-Explosive Devices to Transient Electrical Pulses", NOLTR 61-20, 17 April 1961, Unclassified.

CHARACTERIZATION OF SQUIB, MK 1 MOD 0:
Thermal Stacking from Radar-Like Pulses (U)

1. INTRODUCTION

1.1 The mechanism of initiation of wire bridge electro-explosive devices (EEDs) has been studied at this Laboratory in considerable detail. An electro-thermal model has been proposed (reference (1)) which states that the explosive is triggered when the wire bridge has been raised to a particular temperature by " I^2R ", or ohmic, heating of the bridgewire. Experimental data obtained to date have not required an alteration of the basic premise.

1.2 These studies have been of particular interest to, and have been in large supported by, the HERO (Hazards of Electromagnetic Radiation to Ordnance) program. In assessing the vulnerability of an EED to specific electrical environments, it is desirable to be able to predict the probability of its response to various types of electrical inputs.

1.3 The present report deals with the computation of the temperature-time relationships of the bridgewire of an EED when it is subjected to a radar-like train of RF bursts or pulses. The general theory of the electro-thermal model, the digital computation methods, generalizations, and a nomogram of typical results will be given in this report.

1.4 The Squib, Mk 1 Mod 0, has been studied in great detail by the Naval Ordnance Laboratory. It is considered to be typical or at least analogous to the wire bridge EEDs in general use in the explosives field. Thus, while the theory and detailed computations have been applied directly to this particular EED, it is firmly believed that the work herein can be applied directly, or with little change, to many other specific EEDs. It will therefore be left to the reader to make such adaptations or extensions as may be necessary to suit his individual needs rather than to give a broader and more comprehensive treatment to the subject.

2. THEORY

2.1 The Squib, Mk 1 Mod O, (shown in Figure 1) has been considered as a lumped parameter system. The platinum-iridium bridgewire plus its immediate surroundings (explosive when loaded, air before loading, or explosive simulant when dummy loaded) has a heat capacity represented by C_p . It is assumed that C_p is independent of the bridgewire temperature.

2.2 The dissipation of electrical energy in the bridgewire causes the bridgewire to be elevated in temperature by an amount, θ . The bridgewire is known to be cooler at the ends than in the center because of the cooling of the support posts. For simplicity, the bridgewire temperature is considered to be an average of the temperature along its length. The hottest point on the wire will be the most likely to cause initiation. Yet, experimentally, this hottest point does not differ markedly from the average temperature.

2.3 A steady state condition of electrical energy dissipation in the bridgewire will lead to a corresponding steady state flow of thermal energy into the support posts and into the explosive, or simulant, in contact with the bridgewire. Under these steady state conditions the heat energy flow, and therefore the electrical energy input, will be proportional to the temperature elevation, θ . The proportionality constant, γ , is designated as the heat loss factor.

2.4 These parameters can be combined in an instantaneous energy-balance equation

$$C_p \frac{d\theta}{dt} + \gamma \theta = P(t),$$

where $P(t)$ is the power time function.

From this differential equation $\theta(t)$ functions can be derived which describe the thermal response of the EED bridgewire to various electrical input wave-forms. Experimental verification of the equation is facilitated by the technique of using the EED bridgewire as its own resistance thermometer. The change of bridgewire resistance with temperature can be expressed (using again the idea of lumped constants and of θ as the average bridgewire temperature elevation) by

$$R = \overset{\circ}{R} (1 + \alpha \theta)$$

where $\bar{R}$ is the resistance of the EED at a stated reference temperature.

and α is the corresponding temperature coefficient of resistance measured for a temperature change from this same stated reference temperature.

This relationship is based on the assumption that the resistance varies linearly with the temperature throughout the practical temperature range.

2.5 Because of the low resistance of the EED compared to the probable magnitudes of source impedances that might be expected in weapon circuitry carrying RF power, it was decided to consider the case for constant-current pulse trains. An additional reason for this choice is that, for EEDs with a positive value of the coefficient, α , heating of the bridge-wire raises its resistance and therefore increases the power it absorbs, even though the pulse amplitude is unchanged.* Constant current pulse data would therefore provide a conservative basis for making system safety estimates. The differential equation expressing the lumped parameter behavior under constant current input conditions is:

$$C_p \frac{d\theta}{dt} + \gamma\theta = I^2\bar{R} (1 + \alpha\theta) \quad (1)$$

which can be solved to yield

$$\theta_w = \frac{I^2\bar{R}}{\gamma - I^2\bar{R}\alpha} \left[1 - \exp \left(\frac{I^2\bar{R}\alpha - \gamma}{C_p} \cdot w \right) \right] \quad (2)$$

where W is the pulse length

and θ_w is the temperature at the end of the pulse.

2.6 Whenever the bridgewire temperature is above ambient with no power applied, the differential equation expressing the bridgewire cooling will be found to apply:

$$C_p \frac{d\theta}{dt} + \gamma\theta = 0. \quad (3)$$

*Positive values of α cause constant voltage pulses to deliver less power as the temperature rises, i.e.,

$$P = \frac{E^2}{R(1 + \alpha\theta)} = \frac{\bar{P}}{1 + \alpha\theta}$$

Taking time, t , measured from the instant the power is removed and cooling begins, and taking the bridgewire temperature to be θ_m at the instant $t = 0$, equation (3) can be solved:

$$\theta_c = \theta_m \exp \left[- \frac{\gamma t_c}{C_p} \right] = \theta_m \exp \left[- \frac{t_c}{\tau} \right] \quad (4)$$

where τ , the thermal time constant, equals $\frac{C_p}{\gamma}$,

t_c is the cooling time between current pulses,

and θ_c is the temperature at the end of the cooling time.

2.7 To obtain the temperature-time history of an EED subjected to a train of constant current pulses it is necessary to apply equations (2) and (4) in alternation in as many cycles as may be appropriate to the study.

2.8 If the cooling portion of the cycle is long compared to τ , the bridgewire will return to ambient temperature at the end of the cycle. In this case each cycle will repeat the history of the preceding cycle. If the pulse repetition frequency, that is the frequency at which the pulses are repeated, is increased by decreasing the cooling portion of the cycle beyond a certain point, then at the beginning of the pulse train the loss of heat during cooling will be less than the gain during the heating portion of the cycle. In this case the temperature of the bridgewire will be greater for one cycle than it was for the preceding one. As a result of this increase in temperature both the rise and fall of temperature during the heating and cooling portions of the cycle are increased. However, since the increase in the rise of temperature during the heating portion of one cycle with respect to that of the preceding cycle is linear and the fall in temperature during the cooling portion increases exponentially, the loss of heat due to cooling will eventually become equal to the gain in heat during the heating portion and the temperature of the wire again goes through a stable history from one cycle to the next as shown in Figures 2 and 3. If the input energy in the constant current pulses is high enough then the bridgewire temperature will rise high enough to initiate the explosive surrounding it. If the energy is not high enough the bridge temperature will stabilize at a value lower than the ignition temperature of the surrounding explosive.

3. COMPUTATIONS AND RESULTS

3.1 An IBM 704 Computer was programmed to express the constant current heating with alternate natural cooling. The Fortran Program is given in Appendix A. The input data for the IBM 704 program consisted of the current, the initial resistance, the repetition frequency, the pulse width, and the thermal parameters; γ , α , and C_p . Using these data and equation (2), the program computed the temperature of the bridgewire at the end of the heating portion of the cycle. Having obtained this result equation (4) was used to find the temperature at the end of the cooling portion of the cycle. The resistance of the bridgewire which corresponded to these temperatures was also calculated. The program also computed the energy absorbed in the heating portion of each cycle. The computation was then repeated using the temperature and resistance at the end of the cooling portion of the cycle as the values for the start of the next cycle. After each cycle tests were made of the maximum temperature of the cycle, the increase in this temperature over that of the preceding cycle, and the number of cycles computed. These values were compared with preassigned values of these quantities. Computation ceased after the preassigned number of cycles or if the temperature exceeded the preassigned value for the maximum temperature, which usually was $2,000^{\circ}\text{C}$, or if the increase in temperature over the preceding cycle was less than one half of one percent. Otherwise, computation proceeded to the next cycle.

3.2 The initial resistance in almost all cases was taken to be 1.0 ohm. Pulse repetition frequencies from 60 to 3,000 cycles per second were studied. In most cases the on time for the pulse was short compared with the total time of the cycle and small compared to the thermal time constant τ . Under these conditions the cooling portion of the cycle can be considered to be independent of the pulse width. The temperature rise during a pulse will be a function of the energy. Thus, for any given pulse frequency the same maximum peak temperature will be reached for any combination of current, resistance, and pulse width for which the product I^2RW is constant.

3.3 Results printed out (Figure 4) included the resistance and temperature at the beginning and end of the heating portion of the cycle, the energy of the heating portion of the cycle, and the total energy used in this and previous cycles. Computations were carried out for different combinations of current, pulse repetition frequency, and pulse width selected so as to give maximum peak temperatures of $2,000^{\circ}\text{C}$ or less.

3.4 It was found that if the logarithm of I is plotted against the logarithm of the pulse width for any given frequency and maximum temperature, the result is very nearly a straight line. This was done for several representative frequencies and

is shown in Figures 5 and 6. In each case lines were drawn representing temperatures of 300, 500, and 1,000°C. The results of the calculations can all be combined into a single graph in which the product I^2RW is the ordinate and the pulse repetition frequency is the abscissa. The results can be shown by drawing contour lines representing the attained maximum peak temperature (Figure 7). In order to locate these contour lines it was convenient to use a method of computation which would have a given temperature as part of the input data and calculate the point corresponding to this temperature for some given combination of the other variables.

3.5 Appendix B gives the program as it was modified to accomplish this result. The modified program was arranged to find the pulse width which would give the desired maximum peak temperature for a given pulse repetition frequency. This is done by repeated interpolations between previously determined pairs of values of the pulse width and temperature. The program begins with two pulse widths and their corresponding maximum temperatures. It then interpolates or extrapolates for the pulse width corresponding to the desired temperature. Using this value of the pulse width it then computes the maximum peak temperature as in the previous program. This temperature is compared with the desired temperature. If the difference is less than 5°C, the computation ceases. Otherwise, the new pulse width and temperature replace one of the previous pairs of values and the process is repeated. One of the original pairs of pulse width and temperature values can be taken to be zeros; the other pair may be merely an estimate for which no great accuracy is required. The process will find a satisfactory value for the pulse width within a few iterations.

3.6 Values of I^2RW for frequencies of pulse repetition frequency from twenty to two thousand cycles per second giving maximum peak temperatures of 300, 500, and 1,000°C above ambient temperature were computed in this way and are given in Table 1. These results are also shown graphically with contour lines for the maximum temperatures drawn. In order to simplify the location of the ordinate value for this graph, a simple nomogram was designed which gives the ordinate for known values of I and W with resistance R . The nomogram is shown in Figure 8. These computations used typical values of the thermal parameters: γ , 600 microwatts per degree; α , 705 parts per million per degree* and C_p , 2.4 microjoules per degree. A few calculations were made using a value for α of 900 parts per million per degree. Temperature reached under these conditions are higher

*It should be noted that α is a temperature dependent constant and must be selected to correspond to the base temperature from which resistance calculations are made. If the base temperature or base resistance changes then α must also be changed.

than for the smaller value of α . The difference is greater when comparing the maximum peak temperature than when comparing the first pulses. For the first pulse the difference is of the order of 5%. At higher frequencies the maximum peak temperatures differ by about 15%. Utilization of the computational technique therefore requires a realistic choice of numerical values for the various parameters. Experience to date has shown that the determination of R is less subject to experimental error and is less variable than that of the other parameters. The determination of γ and C_p is the least precise since the error of their determination must include the error of determination of α . The extremes of the individual values of the most variable parameter rarely exceed 0.6 to 1.5 times the central value.

4. CONCLUSIONS

4.1 The results obtained in this investigation have been summarized in Table 1 and as a nomograph (Figure 8). The table gives initial conditions which determine the pulse size required to heat one particular type of bridgewire ultimately to a maximum peak temperature of 300, 500, or 1,000°C above ambient for pulse repetition frequencies from 20 to 2,000 cycles per second. The initial conditions are most conveniently expressed as a pseudo-energy per burst term in units of microjoules per burst. This term is computed on the assumption that the pulse power is maintained at its initial value (the power level before any bridgewire resistance change occurs). The actual pulse energy will, of course, be greater than this due to the heating and corresponding resistance increase of the bridgewire.

4.2 The computed results can be used to assess the expected response of an EED to a particular electromagnetic energization. If values of R , α , γ , and C_p are known for a particular EED, it is possible to compute the interrelationships between: (a) maximum peak temperature, (b) pulse repetition frequency, and (c) initial pulse magnitude (which in turn can be broken down to pulse width and initial pulse amplitude). For instance, for the Squib, Mk 1 Mod 0, a temperature rise of 500°C would be expected at a pulse repetition frequency of 2,000 cycles per second for a 10-ampere pulse with a pulse width of 1.1 microsecond. The same temperature would be attained at pulse repetition frequencies below approximately 30 cycles per second for the same current amplitude provided the pulse width were 10.5 microseconds.

4.3 Once the temperature can be deduced the probability of initiation of the EED can in turn be estimated provided information is available as to the temperature which will cause initiation of the EED. This information usually can be found experimentally from DC pulse firing data. Inference of the

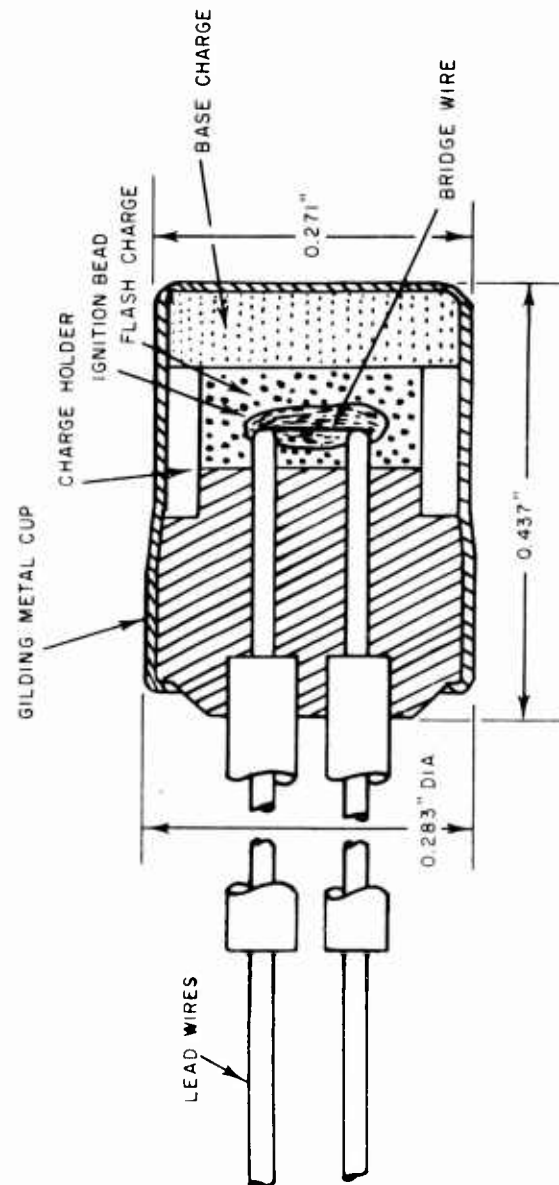
necessary temperature based on the "Hot-Spot" Theory of Bowden and Yoffee (reference (a)) has been found to give satisfactory results (reference (3)).

4.4 Subsequent to the work herein reported a technique was devised to monitor the bridgewire heating and cooling of EEDs being energized by microwave energy from a 9-KMC radar. Qualitative and preliminary quantitative comparison show agreement between results and predicted values indicating that the phenomena of thermal stacking and the appearance of the time-temperature wave-forms as they are described herein are in accord with experiment.

Table 1

Relationship Between I^2_{RW} (microjoules),
Pulse Repetition Frequency, and Equilibrium Peak Temperature

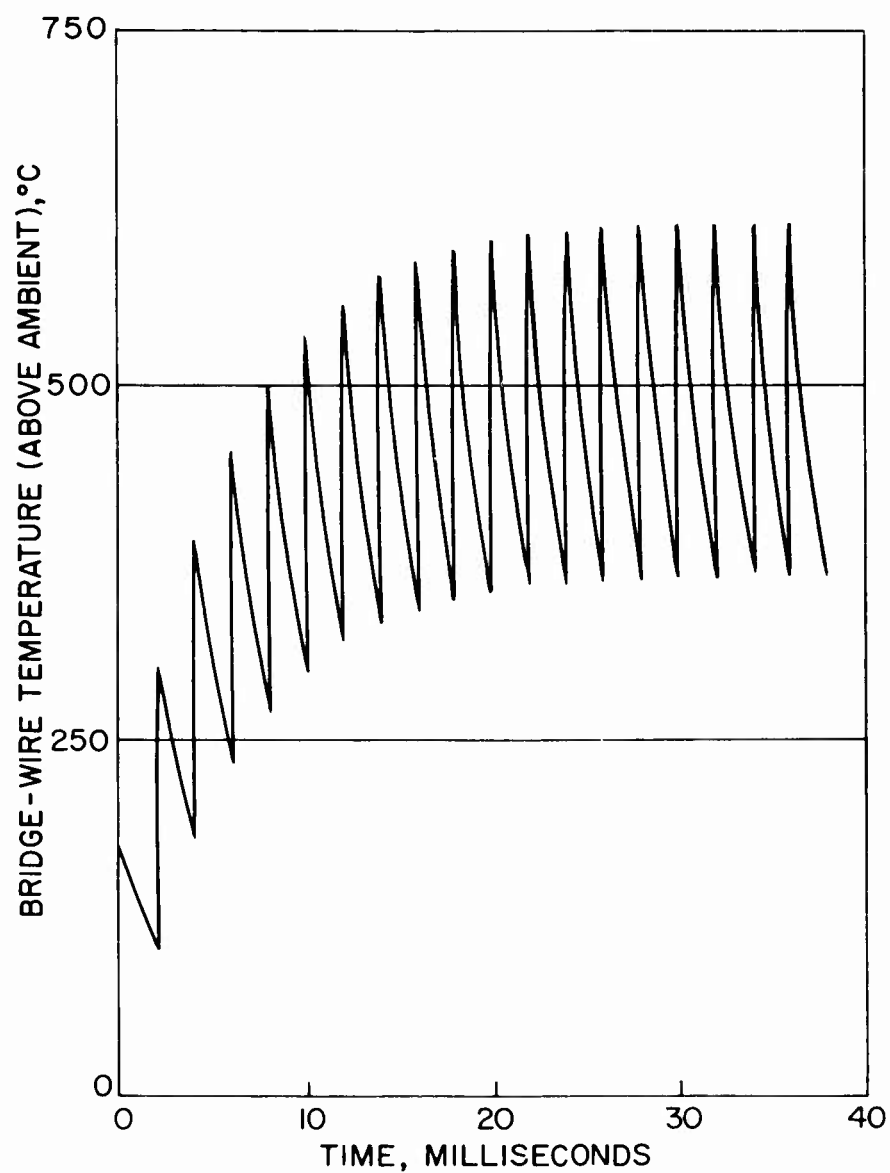
PULSE REPETITION FREQUENCY (cps)	EQUILIBRIUM PEAK TEMPERATURE (°C)		
	300	500	1000
20	653.1	1029.2	1819.9
40	652.3	1026.7	1814.7
60	642.3	1009.8	1778.3
100	594.5	928.4	1608.4
140	530.9	827.7	1408.1
200	452.6	695.1	1156.0
250	398.3	606.8	1019.3
300	353.9	539.4	878.5
600	211.5	315.7	505.0
1000	137.7	205.2	324.3
1400	103.0	152.6	240.1
2000	74.6	110.9	172.4



NOTES:

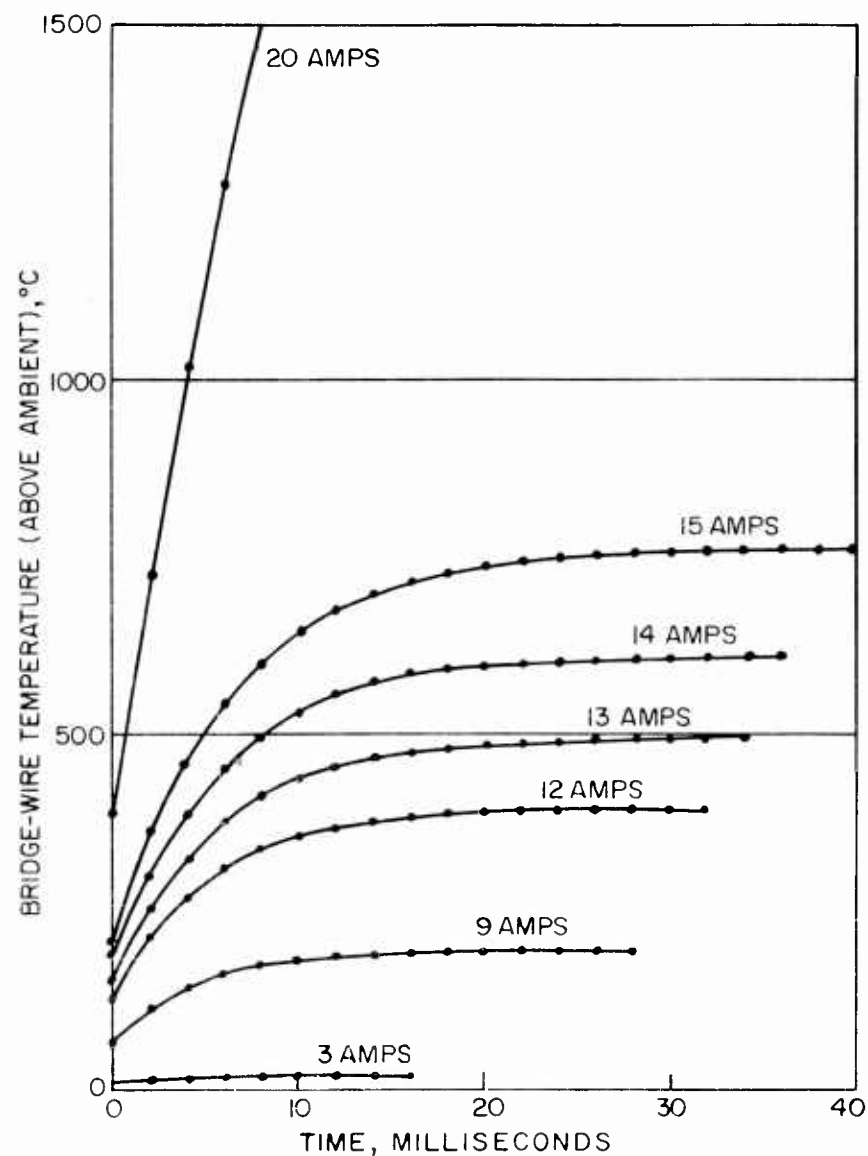
1. IGNITION BEAD - APPROX. 5 MG DDNP/KClO₃
2. FLASH CHARGE - APPROX. 45 MG BLACK POWDER
3. BASE CHARGE - APPROX. 45 MG BLACK POWDER
4. BRIDGE WIRE - 0.001" PLATINUM-IRIDIUM 0.060" LONG

FIG. 1 SQUIB MK I MOD O



NOTE: CONSTANT CURRENT 14AMP,
PULSE REPETITION FREQUENCY 499.5CPS
PULSE WIDTH 2 MICROSECONDS

FIG.2 THERMAL STACKING OF THE SQUIB, MKI BRIDGE



NOTE: CONSTANT CURRENT PULSES APPLIED TO SQUIB, MK I LOADED. PULSE REPETITION FREQUENCY 499.5 CPS PULSE WIDTH, 2 MICROSECONDS.

FIG. 3 THERMAL STACKING AS A FUNCTION OF PULSE AMPLITUDE

			THERMAL PARAMETERS			
CURRENT	RESISTANCE	PULSES	PULSE WIDTH	GAMMA	ALPHA	CEE
AMPS	OHMS	PER SEC	MICROSECONDS	MICWTS/DEG	P/M/DEG	MICJLS/DEG
10.00	1.000	200.00	4.568	600.0	705.0	2.400
CYCLE COUNT						
1						
ELAPSED TIME						
5.00 MILLISEC						
TEMPERATURE						
BEFORE PULSE						
0. DEG C						
AFTER PULSE						
203.59 DEG C						
ENERGY IN PULSE						
TOTAL ENERGY						
RESISTANCE						
BEFORE PULSE						
1.000 OHMS						
AFTER PULSE						
1.144 OHMS						
CYCLE COUNT						
2						
ELAPSED TIME						
10.00 MILLISEC						
TEMPERATURE						
BEFORE PULSE						
58.40 DEG C						
AFTER PULSE						
270.97 DEG C						
ENERGY IN PULSE						
TOTAL ENERGY						
RESISTANCE						
BEFORE PULSE						
1.041 OHMS						
AFTER PULSE						
1.191 OHMS						
CYCLE COUNT						
3						
ELAPSED TIME						
15.00 MILLISEC						
TEMPERATURE						
BEFORE PULSE						
77.72 DEG C						
AFTER PULSE						
293.28 DEG C						
ENERGY IN PULSE						
TOTAL ENERGY						
RESISTANCE						
BEFORE PULSE						
1.055 OHMS						
AFTER PULSE						
1.207 OHMS						
CYCLE COUNT						
4						
ELAPSED TIME						
20.00 MILLISEC						
TEMPERATURE						
BEFORE PULSE						
84.12 DEG C						
AFTER PULSE						
300.67 DEG C						
ENERGY IN PULSE						
TOTAL ENERGY						
RESISTANCE						
BEFORE PULSE						
1.059 OHMS						
AFTER PULSE						
1.212 OHMS						
CYCLE COUNT						
5						
ELAPSED TIME						
25.00 MILLISEC						
TEMPERATURE						
BEFORE PULSE						
86.24 DEG C						
AFTER PULSE						
303.12 DEG C						
ENERGY IN PULSE						
TOTAL ENERGY						
RESISTANCE						
BEFORE PULSE						
1.061 OHMS						
AFTER PULSE						
1.214 OHMS						

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FIG. 4 TYPICAL PROGRAM PRINTOUT OF RESULTS

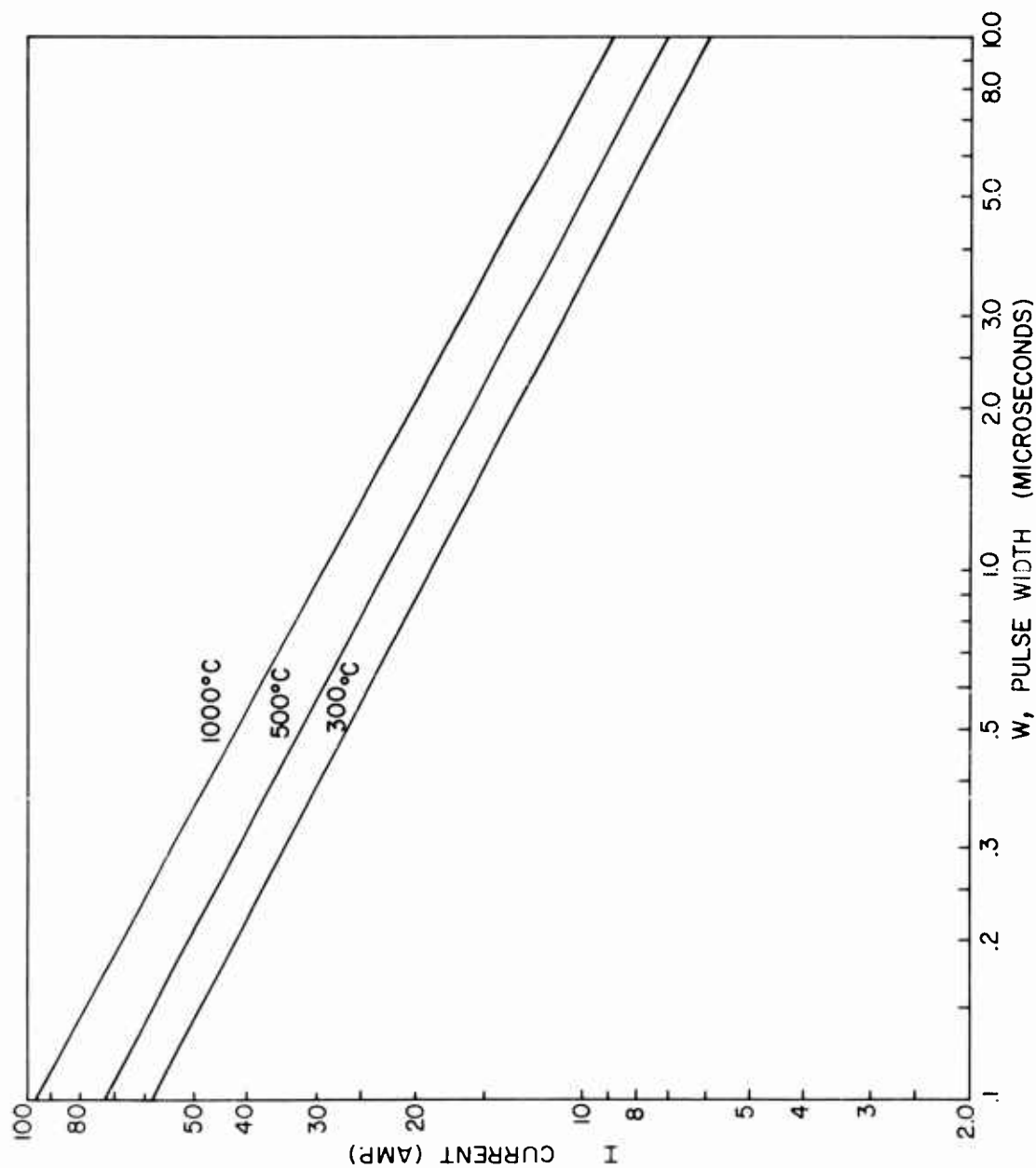


FIG.5 MAXIMUM PEAK TEMPERATURES FOR PULSE REPETITION
FREQUENCY OF 300 CPS

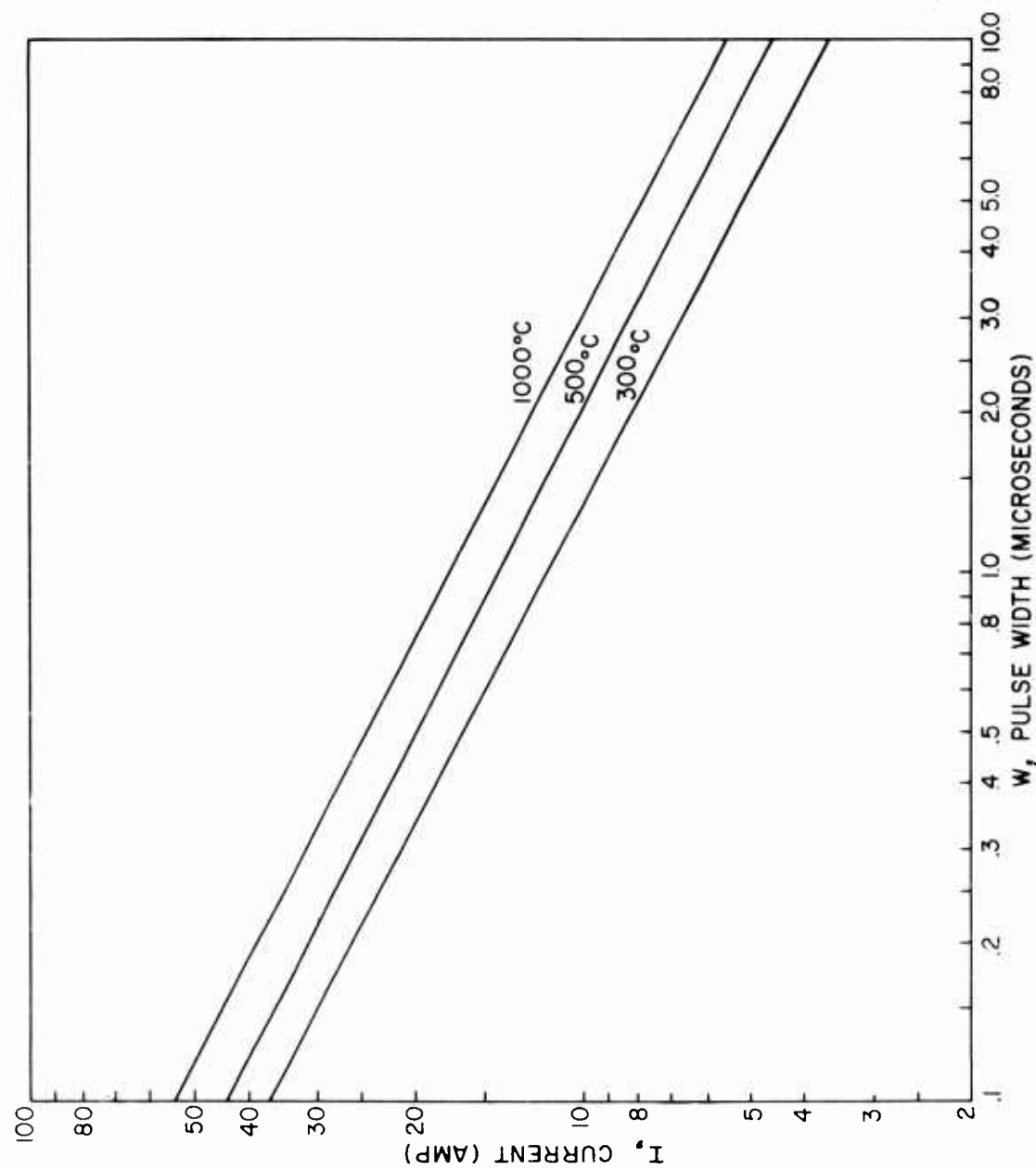


FIG. 6 MAXIMUM PEAK TEMPERATURES FOR PULSE REPETITION FREQUENCY OF 1000CPS

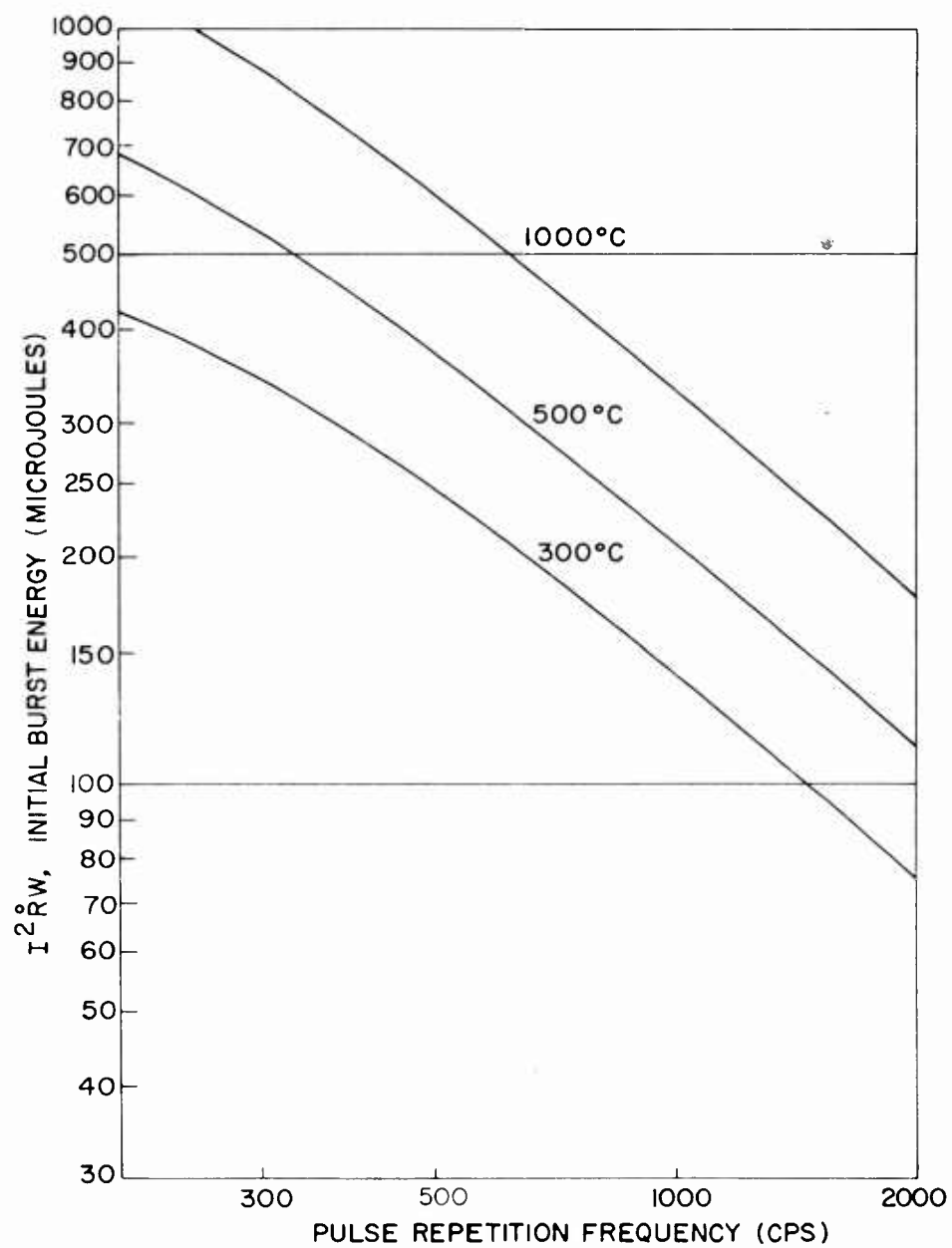
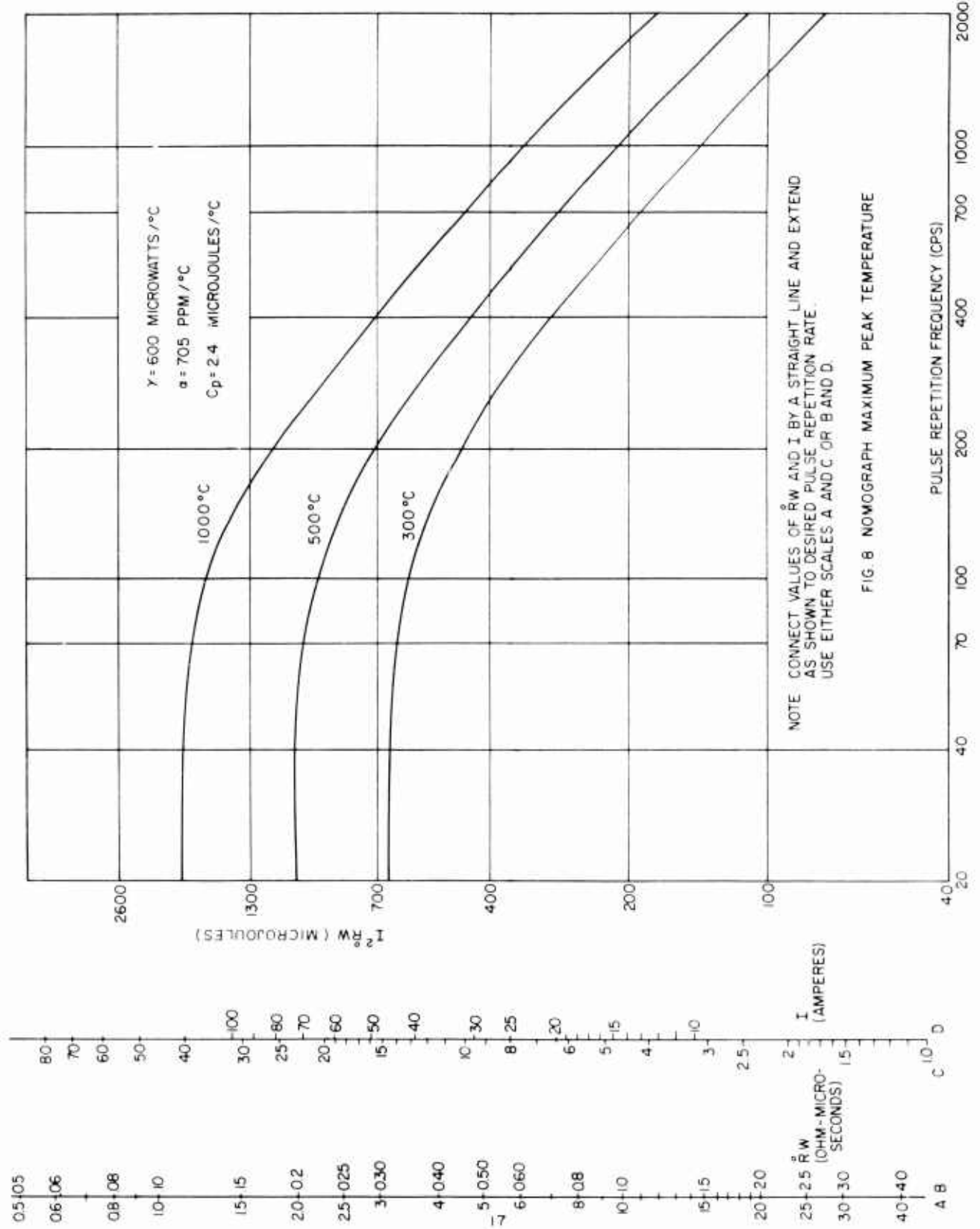


FIG. 7 MAXIMUM PEAK TEMPERATURES AS A FUNCTION OF PULSE PARAMETERS



APPENDIX A

A-1. Fortran II is an Automatic Programming System of Formula Translation. It is a method of rewriting mathematical relations in a symbolic form which can be converted by a high speed digital computer into a productive sequential computational procedure. Fortran II can now be interpreted by a number of different makes of high speed computers.

A-2. Pages A-3 and A-4 are a photographically reproduced copy of the Fortran II listing of the computational program described in Paragraph 3.1. An exact keypunch duplication of this listing, one card per line, including all spaces within each line, should produce a source deck which can be compiled by any activity to whom Fortran II is available.

A-3. A description follows of each of the program symbols of quantities required for the computations.

Program Symbols:	TMAX	Upper bound of computed temperature of EED bridgewire in degrees Centigrade.
	PC	Ratio of maximum temperature attained in one pulse to that of preceding pulse which is considered to represent a stable temperature condition.
	NMAX	Maximum number of pulses to be computed.
	CUR	Constant current in amperes.
	RZ	Initial resistance in ohms.
	RATE	Pulse repetition frequency in cycles per second.
	TP	Time in seconds during which the constant current flows in each pulse.
	GAM	Heat loss factor, Gamma, in watts per degree Centigrade.
	ALF	Temperature coefficient of resistivity, Alpha, in ohms per ohm per degree Centigrade.
	CP	Heat capacity in joules per degree Centigrade.

APPENDIX A (cont'd)

Program
Symbols:

T1	Temperature at the beginning of pulse.
R1	Resistance at the beginning of pulse.
T2	Temperature at end of heating portion of cycle.
R2	Resistance at end of heating portion of cycle.
T3	Temperature at end of cooling portion of cycle.
R3	Resistance at end of cooling portion of cycle.
TLST	Maximum temperature of preceding pulse.
TS	Length of cooling portion of cycle.
PENG	Energy in the pulse.
ENG	Total Energy.
TIME	Total time elapsed.

```

C      PROGRAM FOR FINDING TEMPERATURE-TIME HISTORY OF AN EED SUBJECTED
C      TO CONSTANT CURRENT RADAR-LIKE PULSES

5 READ INPUT TAPE 0,301, TMAX,PC,NMAX
7 NN=0
10 READ INPUT TAPE 0,302,CUR,RZ,RATE,TP,GAM,ALF,CP
11 IF(RATE) 115,115,12
12 IF(1.0-TP*RATE) 115,115,16
16 T1=0.0
17 R1=RZ
19 TLST=T1
20 N=0
21 ENG=0.0
23 TS=1.0/RATE-TP
24 EXP=0.36787944** (TS*GAM/CP)
28 WRITE OUTPUT TAPE 0,304, CUR,RZ,RATE,TP,GAM,ALF,CP
29 NN=NN+5
30 CSC=CUR**2
31 ENZ=RZ*CSC
40 EN=R1*CSC
41 D=EN*ALF-GAM
42 C=CP/D
43 E=2.71828183** (TP/C)
44 A=EN/D
45 N=N+1
46 B=A*ALF
48 ED=E-1.0
50 T2=T1+ED*A
51 T3=T2*EXP
52 R2=RZ*(1.0+ALF*T2)
53 R3=RZ*(1.0+ALF*T3)
60 PENG=EN*TP+B*(C*ED-TP)*ENZ
62 ENG=ENG+PENG
74 AN=N
75 TIME=AN/RATE
76 IF(NN-40) 79,79,77
77 WRITE OUTPUT TAPE 0,307, N,PENG
   NN=0
78 GC TO 80
79 WRITE OUTPUT TAPE 0,308, N,PENG
80 WRITE OUTPUT TAPE 0,309,TIME,ENG
81 WRITE OUTPUT TAPE 0,310
82 WRITE OUTPUT TAPE 0,311,T1,R1
83 WRITE OUTPUT TAPE 0,312,T2,R2
84 PX=(T2+273.0)/(TLST+273.0)
86 IF(TMAX-T2) 7,7,87
87 IF(PC-PX) 88,7,7
88 IF(NMAX-N) 7,7,90
90 R1=R3
91 TLST=T2
92 T1=T3
93 NN=NN+6
95 GC TO 40
115 CALL RETURN
116 STOP
301 FCRMAT(F9.0,F9.4,19)
302 FCRMAT(3F8.0,4E11.4)
304 FCRMAT(1H164(1H )18HTHERMAL PARAMETERS/10(1H )78HCURRENT RESIST
   IANCE PULSES PULSE WIDTH GAMMA ALPHA CEE PEE/12(1 304
   2H )78HAMPS CHMS PER SEC MICROSECONDS MICWTS/DEG P/ 304

```

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3M/DEG MICJLS/DEG/F16.2,F13.3,F11.2,6PF14.3,2F11.1,F12.3)
 307 FCRMAT(1H116(1H)11CYCLE COUNT110,13(1H)15HENERGY IN PULSE3PF11.
 13,12H MILLIJCULES)
 308 FCRMAT(1H016(1H)11CYCLE COUNT110,13(1H)15HENERGY IN PULSE3PF11.
 13,12H MILLIJCULES)
 309 FCRMAT(17(1H)12HELAPSED TIME3PF12.2,25H MILLISEC TOTAL ENERGY
 1F11.3,12H MILLIJCULES)
 310 FCRMAT(17(1H)11TEMPERATURE23(1H)10HRESISTANCE)
 311 FCRMAT(19(1H)12HBEFORE PULSEF10.2,24H DEG C BEFORE PULSE
 1F12.3,5H OHMS)
 312 FCRMAT(19(1H)11HAFTER PULSEF11.2,23H DEG C AFTER PULSE
 1F13.3,5H OHMS)

APPENDIX B

B-1. Appendix B contains the Fortran II listing for the computational program described in Paragraph 3.5 together with a listing of symbols used in this program which were not used in the first program. The list of symbols given in Appendix A applies to this program as well as that in Appendix A. The computational program consists of a main program and a sub-routine. A photographically reproduced copy of the listing for these programs is given following the list of symbols.

Program		
Symbols:	TBS	Maximum peak temperature in degrees Centigrade.
	TP1	First pulse width in seconds.
	TEMP1	Maximum peak temperature in degrees Centigrade which corresponds to a pulse width of TP1.
	TP2	Second pulse width in seconds.
	TEMP2	Maximum peak temperature in degrees Centigrade which corresponds to a pulse width of TP2.

TP1 and TEMP1 may both be zeros. If it is known that one pair of estimates is better than the other this pair should be selected as TP2 and TEMP2.

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C MAIN PROGRAM FOR FINDING PULSE LENGTH WHICH WOULD GIVE A STATED
C FINAL TEMPERATURE USES SUBROUTINE TEMP(TP,T2)

```

COMMON TMAX,PC,NMAX,GAM,ALF,CP,CUR,RZ,RATE
5 READ INPUT TAPE 0,101, TMAX,PC,NMAX,GAM,ALF,CP
10 READ INPUT TAPE 0,102,CUR,RZ,RATE,TBS,TP2,TEM2,TP1,TEM1
11 IF(RATE) 40,40,12
12 N=0
25 TP=TP2+(TBS-TEM2)*(TP2-TP1)/(TEM2-TEM1)
30 TP1=TP2
31 TEM1=TEM2
32 TP2=TP
33 N=N+1
34 CALL TEMP(TP2,TEM2)
35 IF(N-5) 38,38,10
38 IF(ABS(TEM2-TBS)-5.0) 10,10,25
40 CALL RETURN
45 STOP
101 FCRMAT(F8.0,F8.4,I8,3E11.4)
102 FCRMAT (4F8.0,2(E11.4,F8.2))

```

C SUBROUTINE FOR USE WITH PRECEDING PROGRAM

```

SUBROUTINE TEMP(TP,T2)
COMMON TMAX,PC,NMAX,GAM,ALF,CP,CUR,RZ,RATE
7 NN=0
12 IF(1.0-TP*RATE) 115,115,16
16 T1=0.0
17 R1=RZ
19 TLST=T1
20 N=0
21 ENG=0.0
23 TS=1.0/RATE-TP
24 EXP=0.36787944**(TS*GAM/CP)
28 WRITE OUTPUT TAPE 0,304, CUR,RZ,RATE,TP,GAM,ALF,CP
29 NN=NN+5
30 CSC=CUR**2
31 ENZ=RZ*CSC
40 EN=R1*CSC
41 D=EN*ALF-GAM
42 C=CP/D
43 E=2.71828183**(TP/C)
44 A=EN/D
45 N=N+1
46 B=A*ALF
48 EC=E-1.0
50 T2=T1+ED*A
51 T3=T2*EXP
52 R2=RZ*(1.0+ALF*T2)
53 R3=RZ*(1.0+ALF*T3)
60 PENG=EN*TP+B*(C*EC-TP)*ENZ
62 ENG=ENG+PENG
74 AN=N
75 TIME=AN/RATE
76 IF(NN-40) 79,79,77
77 WRITE OUTPUT TAPE 0,307, N,PENG

```

```

NN=0
78 GC TO 80
79 WRITE CUTPUT TAPE 0,308, N,PENG
80 WRITE CUTPUT TAPE 0,309,TIME,ENG
81 WRITE CUTPUT TAPE 0,310
82 WRITE CUTPUT TAPE 0,311,T1,R1
83 WRITE CUTPUT TAPE 0,312,T2,R2
84 PX=(T2+273.0)/(TLST+273.0)
86 IF(TMAX-T2) 89,89,87
87 IF(PC-PX) 88,89,89
88 IF(NMAX-N) 89,89,90
89 RETURN
90 R1=R3
91 TLST=T2
92 T1=T3
93 NN=NN+6
95 GC TO 40
115 CALL RETURN
116 STOP
304 FCRMAT(1H16(1H)18HTHERMAL PARAMETERS/10(1H)78HCURRENT RESIST
TANCE PULSES PULSE WIDTH GAMMA ALPHA CEE PEE/12(1
2H)78HAMPS OHMS PER SEC MICROSECONDS MICWTS/DEG P/
3M/DEG MICJLS/DEG/F16.2,F13.3,F11.2,6PF14.3,2F11.1,F12.3)
307 FCRMAT(1H16(1H)11HCYCLE COUNT110,13(1H)15HENERGY IN PULSE3PF11.
13,12H MILLIJCLES)
308 FCRMAT(1H016(1H)11HCYCLE COUNT110,13(1H)15HENERGY IN PULSE3PF11.
13,12H MILLIJCLES)
309 FCRMAT(17(1H)12HELAPSED TIME3PF12.2,25H MILLISEC TOTAL ENERGY
1F11.3,12H MILLIJCLES)
310 FCRMAT(17(1H)11HTEMPERATURE23(1H)10HRESISTANCE)
311 FCRMAT(19(1H)12HBEFORE PULSEF10.2,24H DEG C BEFORE PULSE
1F12.3,5H OHMS)
312 FCRMAT(19(1H)11HAFTER PULSEF11.2,23H DEG C AFTER PULSE
1F13.3,5H OHMS)

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