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CHARACTERIZATION OF SQUIB MK 1 MOD 0:
SENSITIVITY TO 9 GC RADAR IN THE
NEAR FIELD

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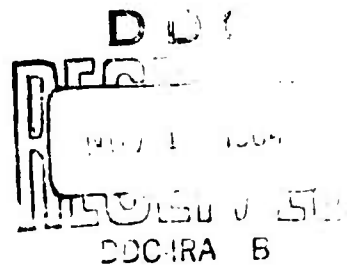
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NOL

28 SEPTEMBER 1964

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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CHARACTERIZATION OF SQUIB MK 1 MOD 0:
SENSITIVITY TO 9 GC RADAR IN THE NEAR FIELD

By
Gary P. Carver

ABSTRACT: Power delivered by a radar set at 9 Gc was coupled to the Mk 1 squib by using the squib leads as $3/2 \lambda$ dipoles placed at the mouth of a micro-wave horn. Bridgewire temperatures were measured by injecting DC current at the RF voltage null points on the dipoles. Temperatures for firings averaged 230°C. 400°C was expected. Though some temperature oscillograms showed normal thermal stacking, there were many cases indicating variation of coupling or internal flow of RF energy.

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Characterization of Squib Mk 1 Mod 0: Sensitivity to
9Gc Radar in the Near Field

This report describes an extension of previous work studying the response of the Mk 1 Mod 0 Squib to 9Gc radar pulses. The work was sponsored by the HERO Program, Task NOL 443.

The results should be of particular interest to those attempting to correlate probability of EED firing with the EED bridgewire temperature at micro-wave frequencies since this work reinforces the idea that such a correlation may be tenable only in part.

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Captain, USN
Commander



C. J. ARONSON
By direction

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INTRODUCTION

One task of the Naval Ordnance Laboratory, White Oak, under the HERO program is to investigate the response of EED's to different types of electrical stimuli. A mathematical model (termed the electro-thermal model) has been formulated for bridgewire squibs which describes the temperature/resistance/time behavior of the bridgewire in terms of the thermal characteristics of the squib^{1,2*}. Techniques for determining the necessary thermal parameters have been developed along with safe and accurate instrumentation designed specifically for this purpose^{3,4,5}.

The Squib, Mk 1 Mod 0, was chosen for the NOL studies because it was involved in accidental RF firings of 2.75-inch rockets and is considered typical of bridgewire type initiators currently in use. Experimental work with the Mk 1 Squib, including constant voltage and constant current DC firing, capacitor discharge firing, and 0 to 5 megacycle AC firing, has supported the predictions of the model⁶⁻¹².

However, in the Summer of 1962, the first serious deviation of results from predictions based on the electro-thermal model was brought to light in Reference 13. The bridgewire temperatures of fully loaded Squibs Mk 1 Mod 0, fired in a wave-guide by irradiation with 9Gc radar were much lower than expected. It was also reported that a considerable amount of power was absorbed other than in the bridgewire. It was hypothesized that initiation was probably due to mechanisms other than ohmic heating of the bridgewire, a basic assumption of the electro-thermal model. An alternate hypothesis exists: the irradiation time is so long that the hot-spot theory must be adjusted to allow for the fact that the firing temperature decreases as the quantity of heated explosive increases and the heating time increases. Whether or not the power absorption in portions of the EED other than the bridgewire would be necessary for anomalous initiations remained to be proved.

Figure I** shows what is meant by the term "thermal stacking". This response pattern is expected when squibs are subjected to pulse radar energy. A more detailed discussion can be found in Reference 13.

* References are on page 21.

** These are theoretical curves for a repetition rate of 500 pps. The data in this report are at 400 pps.

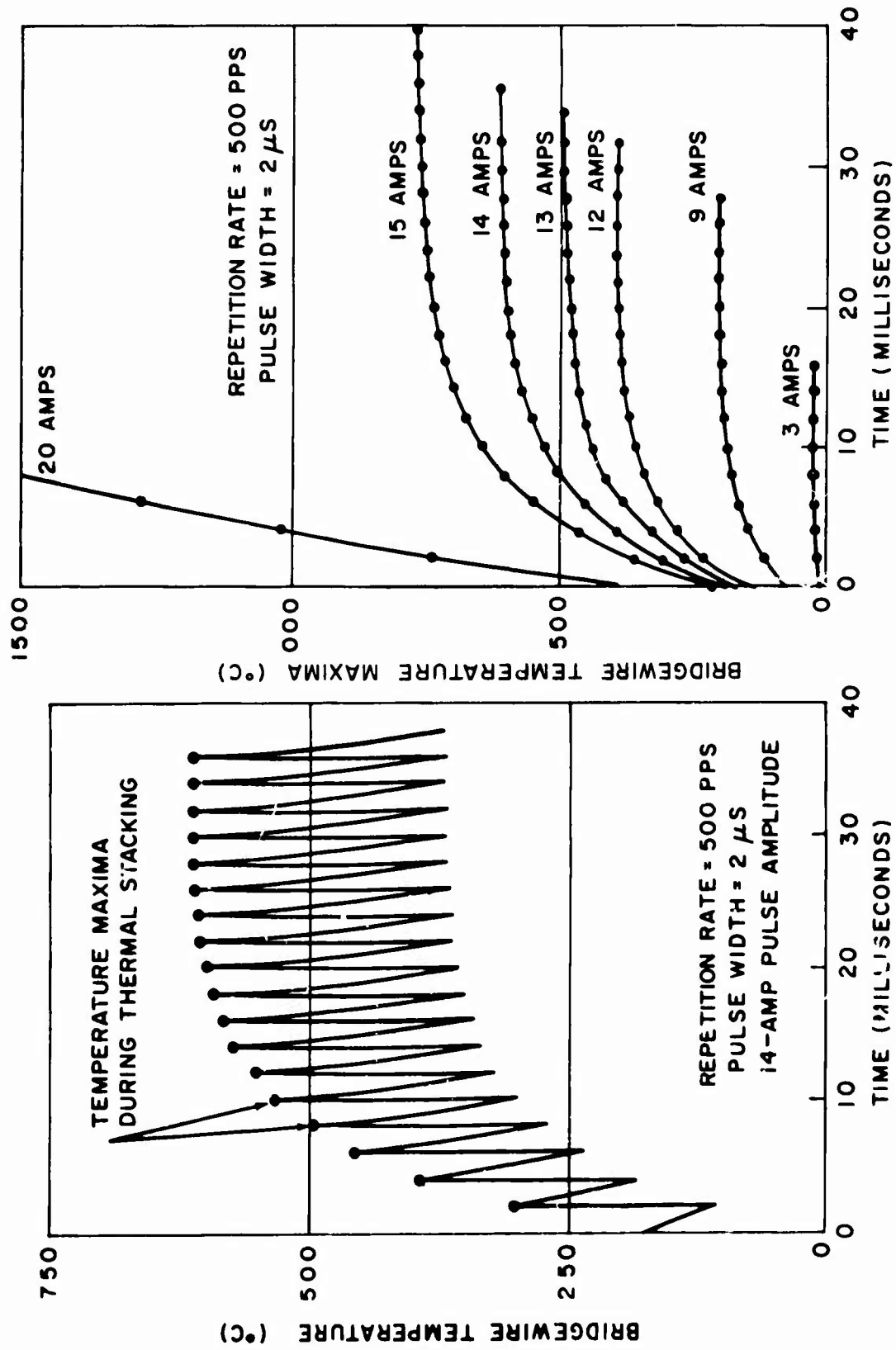


FIG. 1 REPRESENTATIVE THERMAL STACKING CURVES OF THE SQUIB, MK I MOD O, BRIDGEWIRE

The study reported herein was conducted to determine whether or not the low temperature firings by radar were peculiar to the experimental setup and, if not, to attempt to discover the general mechanism(s) responsible for the low temperature initiation.

EXPERIMENTAL PROCEDURE AND APPARATUS

The temperature coefficient of resistance, M , for each of the 100 squibs used in this study was determined by measuring each bridgewire resistance at temperatures of approximately 80 and 0°C. A copper-constantan thermocouple attached individually to each squib was used to record the temperature of the unit while resistance measurements were made on the self balancing bridge.¹ The data were processed on an IBM 7090 computer which calculated M^* and γ for each squib where

$$M = \frac{\Delta R}{\Delta T} \quad \text{and} \quad \gamma = \frac{I^2(R + \Delta R)M}{\Delta R}.$$

For the radar tests the leads of the squibswere cut so that the distance between their ends when spread apart was 4.5 cm. This effectively made the squibs into 3/2 wavelength dipole antennas. (A discussion of the experimental observations which led to this approach and a short explanation of basic theory may be found in Appendix A and Figure 2.) Two-inch lengths of 22 gauge uninsulated wirewere carefully soldered onto the squib leads at the voltage nodes a distance of 6.5 millimeters from each end. Connection was made to these "Lecher" wires (parallel transmission line) for the small DC monitoring current. Figure 3 shows the squib ready for firing.

The squibs were held inside the firing chamber by a specially constructed tool that tightened onto the squib body but provided no electrical connection to the chamber or to the circuitry. (Figures 4, 5, and 6) A wooden dowel from the holder came through a small hole in the firing chamber and was in turn held in position by a clamp. The

* Where M is the rate of change of bridgewire resistance with temperature,
 γ is the heat-loss factor (power dissipated per degree temperature elevation),
 R is the resistance at ambient temperature
 ΔR is the resistance elevation due to
 ΔT , the temperature above ambient.

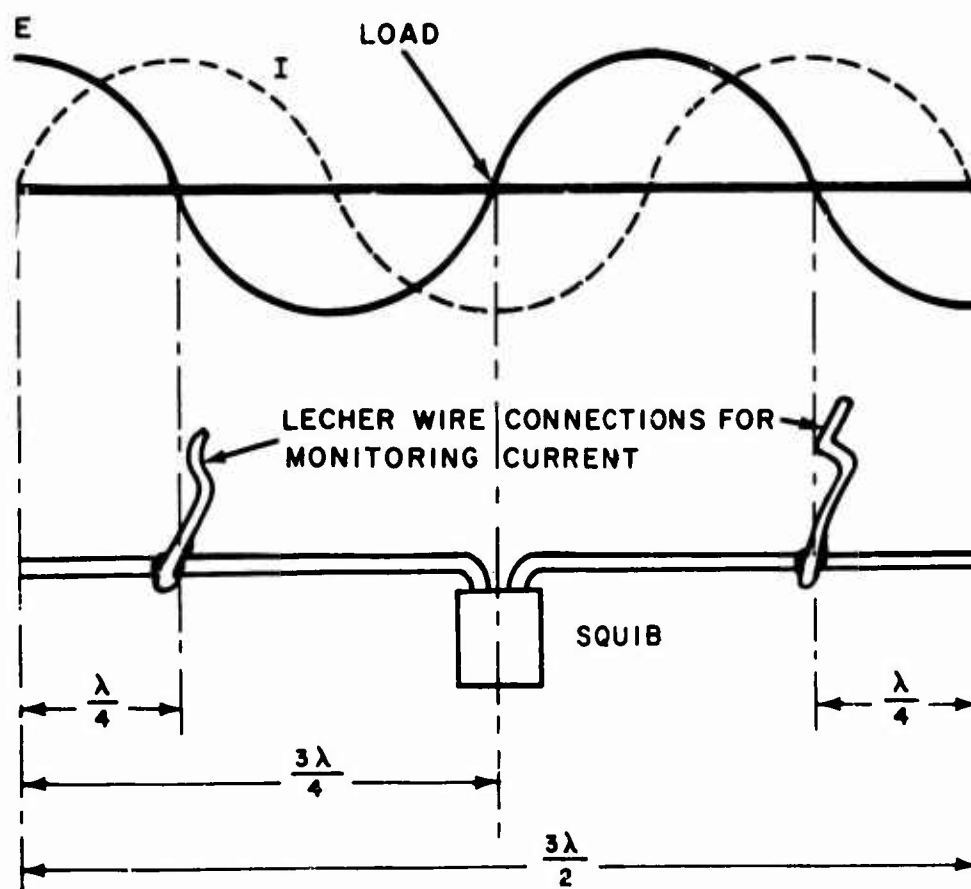


FIG. 2 VOLTAGE AND CURRENT DISTRIBUTION IN A THREE HALVES WAVELENGTH DIPOLE ANTENNA

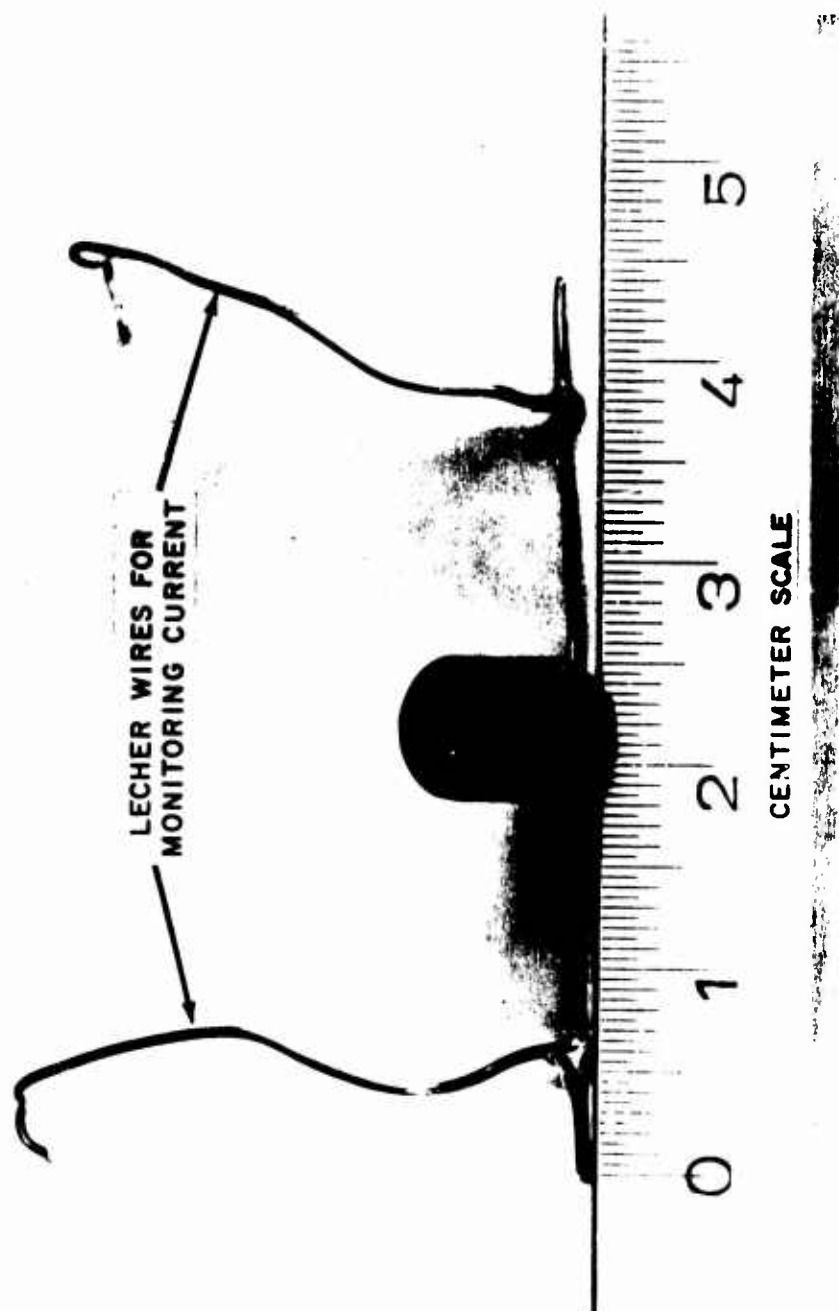


FIG. 3 SQUIB PREPARED FOR FIRING



FIG. 4 EXPLODED VIEW OF HOLDER AND SQUIB

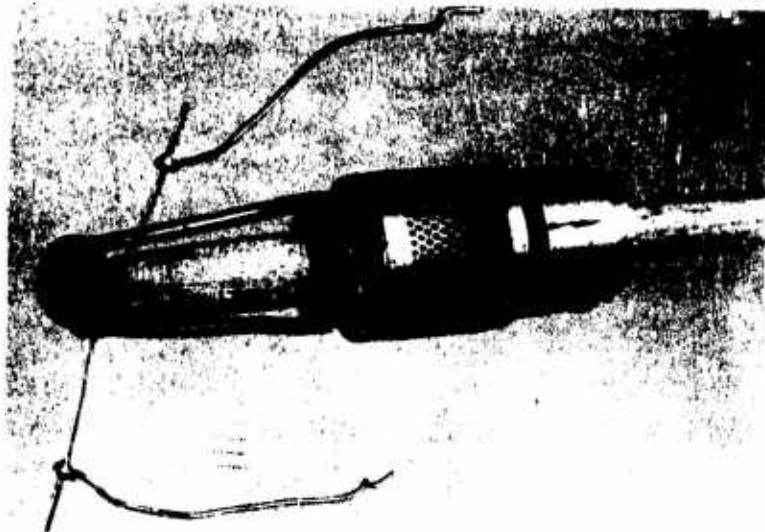


FIG. 5 SQUIB FASTENED IN HOLDER (BOTTOM)

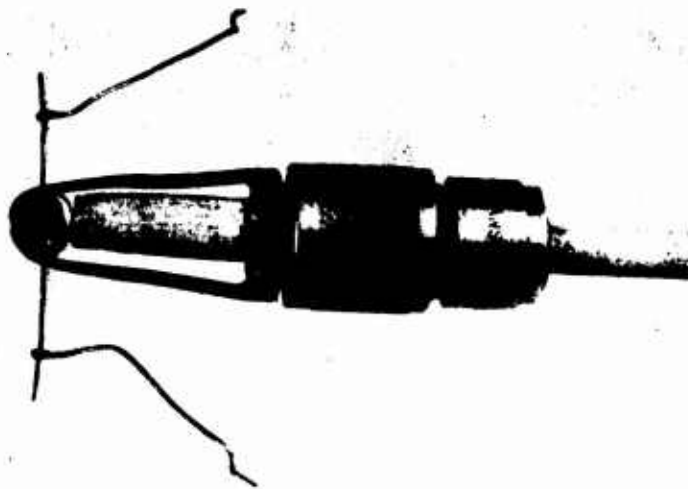


FIG. 6 SQUIB FASTENED IN HOLDER (TOP)

squibs were mounted with their leads spread apart somewhat less than 180° in the plane of the E-field. Connections for the monitoring current were made with alligator clips. The Lecher wires were at right angles to the squib leads. The equipment is shown in Figures 7 and 8.

The squibs were irradiated by a 3db horn*. RF power was supplied by the modulator and transmitter of a Navy 50 12 M X-band mobile radar unit operating at a frequency of approximately 9Gc and at a pulse repetition rate (PRR) of 400 pps. The signal was on for two microseconds and off for 2.5 milliseconds. Peak power was approximately 50kw resulting in an average of 3 watts per square centimeter at the end of the horn. (Peak field intensity at the mouth of the horn is then 24 volts per centimeter.) A section of X-band rectangular wave-guide carried the RF directly from the magnetron to the pyramidal horn. Figure 9a shows a block diagram of the experimental setup.

The 100 units were submitted to the M-determination, had their leads cut to length, the Lecher wires attached, and assigned in random sequence to the firing program. Sixty-eight of these 100 squibs were exposed to the 9Gc radiation. Exposure lasted for 50 milliseconds (40 pulses) and was repeated, if necessary, at intervals of two, and then ten, minutes. If a squib did not fire by the third exposure, it was discarded and noted as a "fail".

Simulated radar firings by constant current of about 1.8 amps and a pulse width of 125 microseconds, and a PRR of 400 per second were carried out on the remaining 32 squibs of the original 100. A block diagram of the apparatus is shown in Figure 9b. A picture of a typical pulse is reproduced in Figure 10a, and the resultant thermal stacking is shown in Figure 10b.

OBSERVATIONS AND RESULTS

The results for the 68 test firings of the Squibs exposed to 9Gc radar, are presented graphically in Figures 11 and 12. A total of 35 squibs fired in the experiment: 27 during the first exposure, five during the second exposure, and six during the third.

* Microwave horns are rated by comparing the signal at a given distance directly in front of the horn with the expected signal level from a spherically uniform radiating point source.

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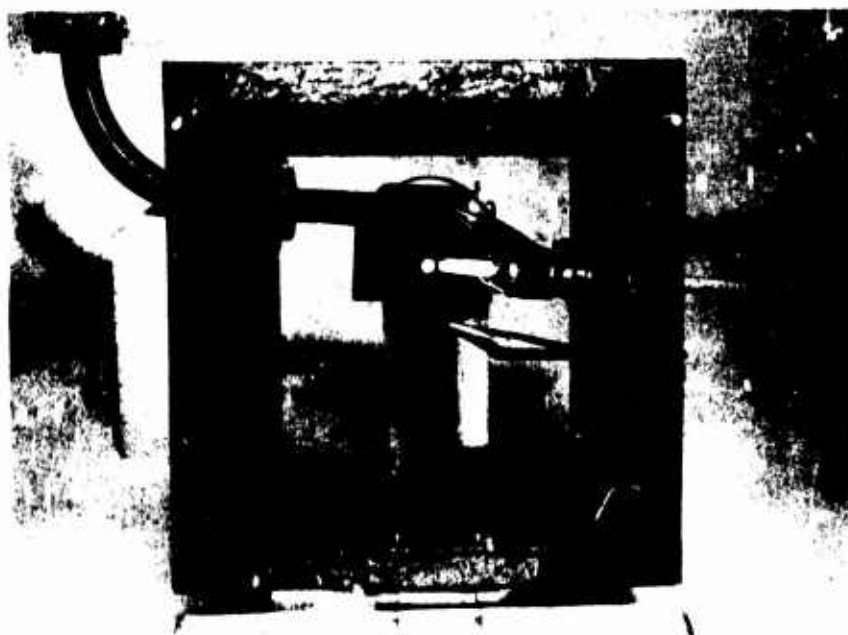
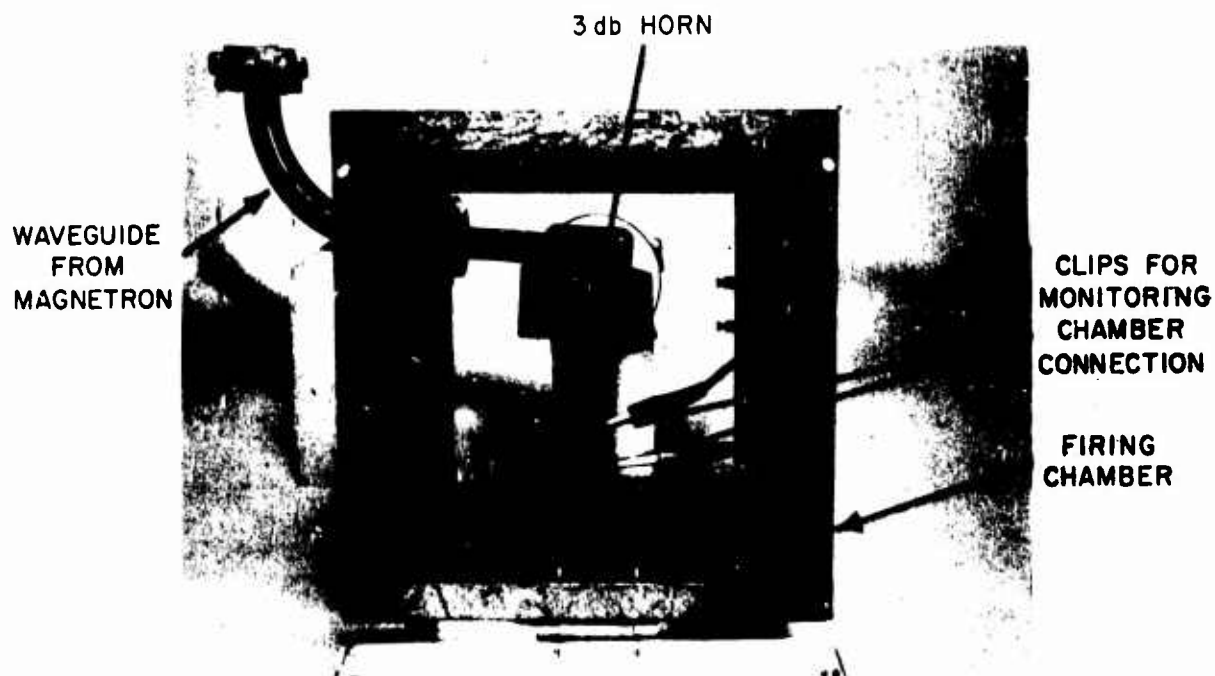
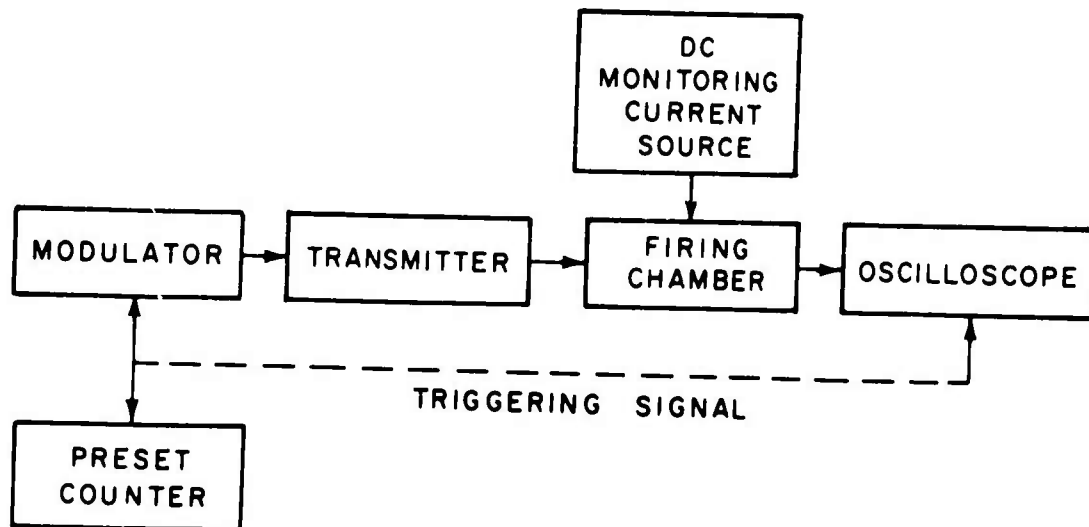
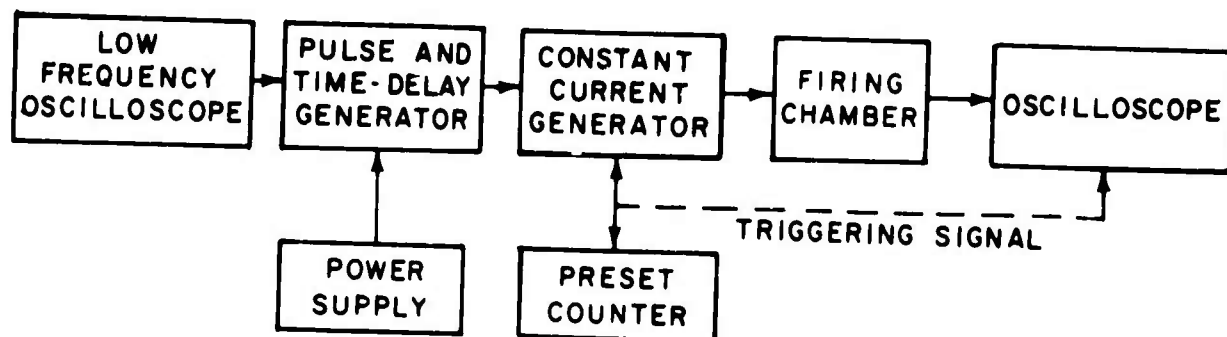


FIG. 8 SQUIB IN PLACE READY FOR FIRING

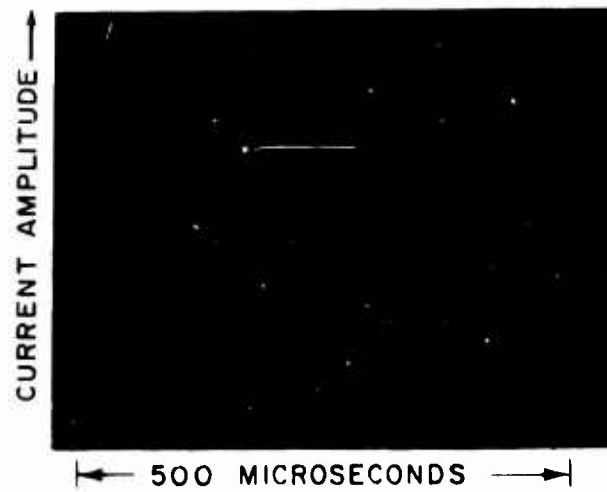


(a) RADAR FIRING APPARATUS BLOCK DIAGRAM

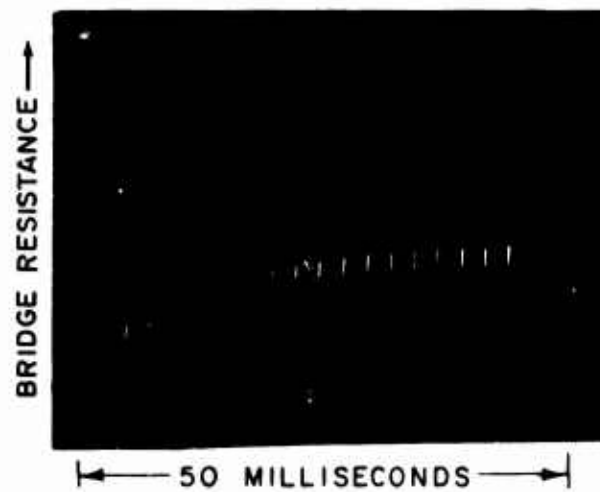


(b) SIMULATION FIRING APPARATUS BLOCK DIAGRAM

FIG. 9 BLOCK DIAGRAMS OF APPARATUS



(a) TRACE OF ONE PULSE FROM SIMULATION EQUIPMENT



(b) THERMAL STACKING DUE TO DC SIMULATION PULSES

FIG. 10 SIMULATION PULSING OSCILLOGRAMS

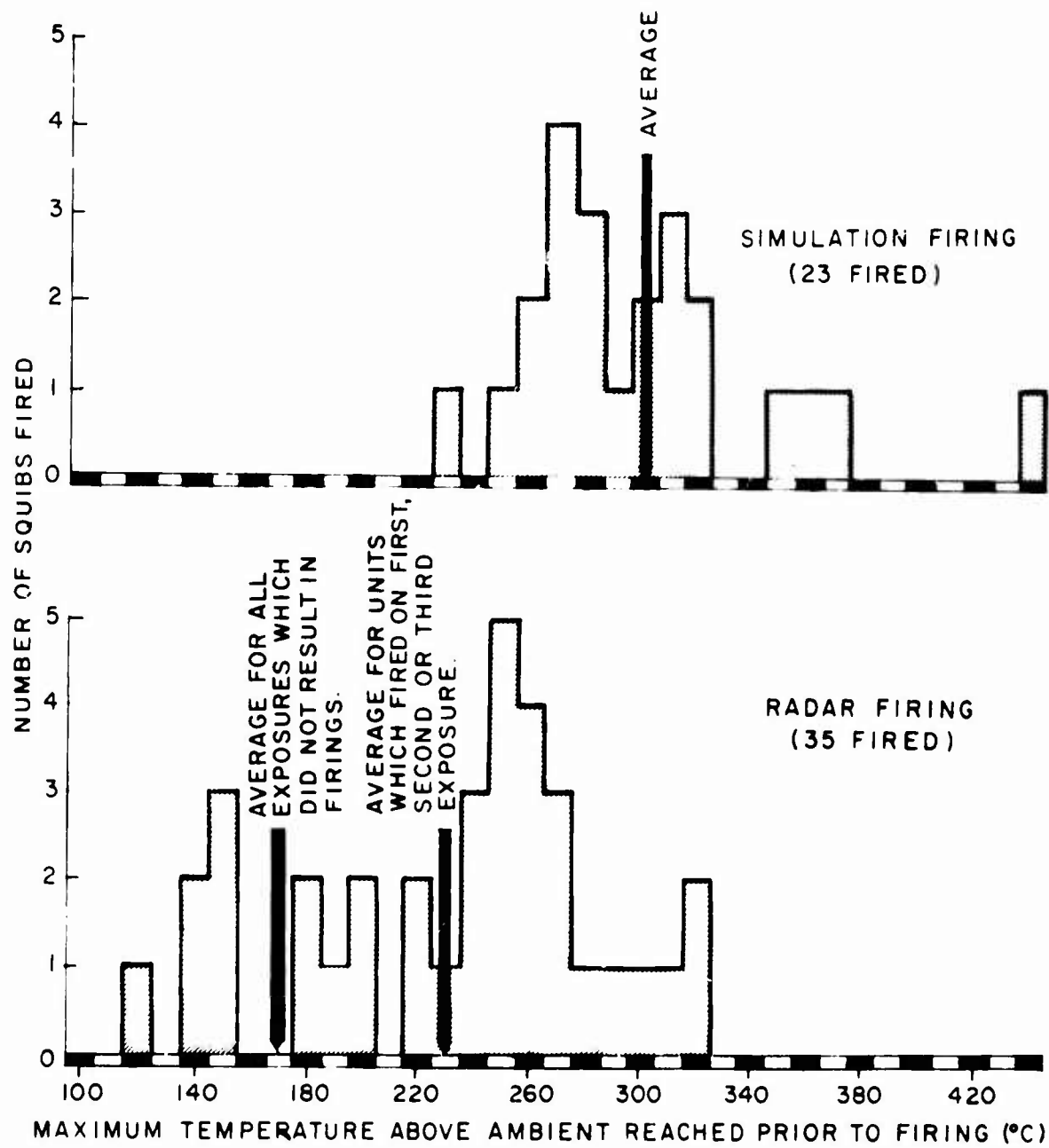


FIG. II GRAPHS SHOWING DISTRIBUTION OF TEMPERATURES OF FIRING

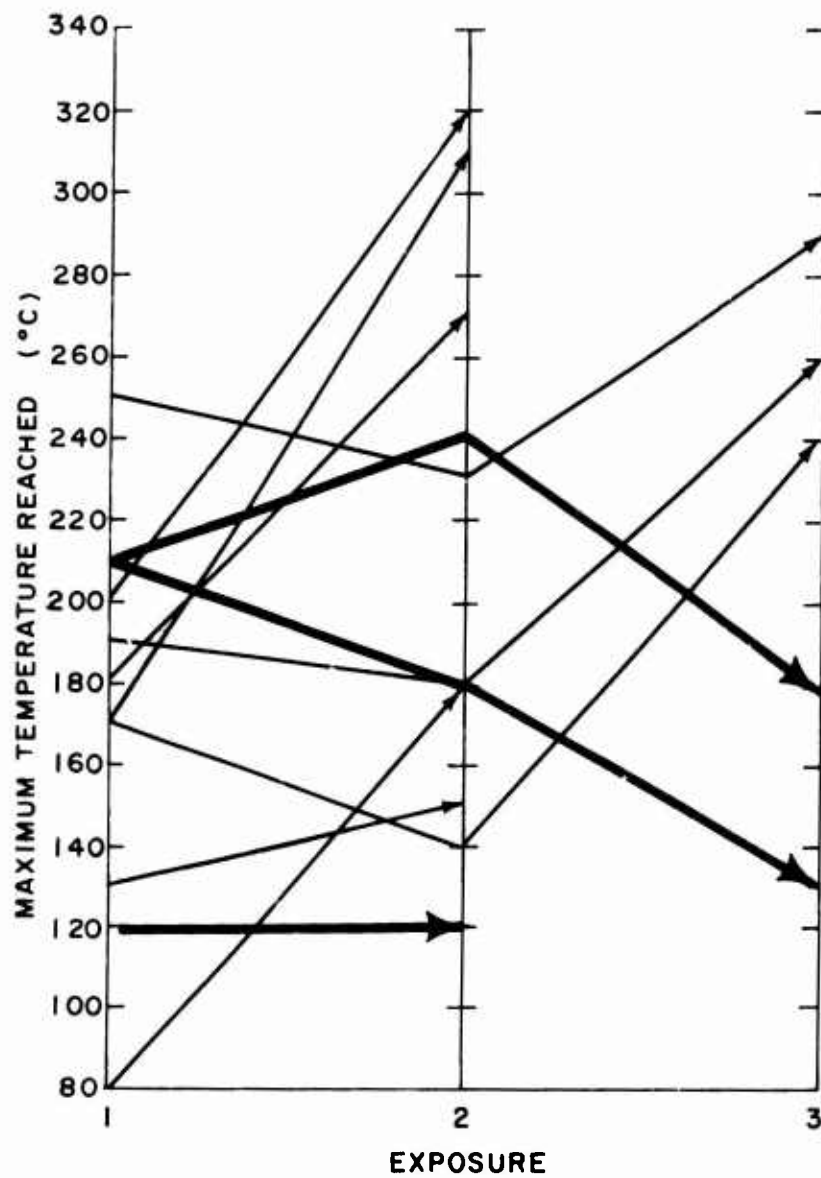


FIG. 12 MAXIMUM TEMPERATURES REACHED BY THE ELEVEN SQUIBS THAT FIRED ON THE SECOND OR THIRD EXPOSURE

A small number of squibs, modified by removal of the copper cup and base charge, were also tested under the same conditions. Incidence of firing and highest temperature reached before initiation were comparable with those obtained using the fully loaded squibs. While the results are not represented in the graphical analysis, the observed behavior of these few modified squibs will be discussed as it does shed some light on the characteristics of RF firing of fully loaded units.

The radar simulation (DC) equipment successfully duplicated the thermal stacking process. Of the 32 squibs tested on the DC pulsing apparatus, 23 fired. The comparison between maximum temperatures reached prior to firing of the two groups is already illustrated in Figure 11.

A typical oscillogram showing the thermal stacking achieved with the pulsing equipment was shown in Figure 10b. Each vertical line is actually a pulse whose peak is proportional to the maximum temperature reached by the bridgewire during that pulse. The initial rising, then leveling off, of the peaks is characteristic of the thermal stacking process. The cooling period does not appear since there is no "monitoring current" between pulses, and the voltage across the bridgewire drops to zero. (The base line was set below the screen to permit greater amplification for improved trace resolution.) Temperature calculations are similar to those for the radar tests as explained in Appendix C.

DISCUSSION OF RESULTS

Unusually low bridgewire temperature firings have been observed. The results verify the evidence previously reported in NOLTR 62-77, that the mathematical model, or more likely the basic assumptions (such as the firing temperature) is not applicable at frequencies as high as 9Gc. In addition, the major problem encountered in the earlier study, i.e., the high voltages between the H-plane faces of the wave-guide has been eliminated because the present studies took place outside the wave-guide.

The calculated maximum temperatures (above ambient) reached prior to firing by the bridgewires of the squibs that initiated ranged from a low of 120°C up to 320°C. The average was 230°C. This average is 70° lower than that obtained on the DC simulation equipment and only about half the 400 - 500°C expected for firing by other types of electrical stimuli under adiabatic conditions.

The data may be treated in another way. Statistical methods patterned after the techniques of Golub and Grubbs¹⁵ have been developed by NOL for handling Go/No-Go data where the stimulus cannot be determined before the experiment but can be measured during or after the experiment. The NOL method permits use of the logistic where the Golub and Grubbs analyses require an underlying normal distribution. By this method it is possible to compute a temperature at which 50% response would be expected, provided we assume that the observed temperatures are Go/No-Go data.* In the accompanying table we compare: (1) the results of processing the data on the assumption that the observed temperatures were the critical levels, with (2) the results assuming Go/No-Go data. In the next to the last column, the column heading, α , is the variability parameter in the logistic distribution function which is comparable to s , the standard deviation of the Gaussian distribution function. Near the 50% firing point α is about 3/5 as big as s for distributions with the same slope.

Group	Temperature in °C					
	Assume continuous data			Assume Go/No-Go data		
	Average	s	sm	50% response	α	sm
First Radar Exposure	239	51	10	206	23	9
Second Radar Exposure	225	86	35	263	42	34
Third Radar Exposure	222	33	15	243	30	25
DC Simulated Radar	292	32	7	250	only one mixed level, no basis for estimating α or sm	

- * The process of analysis of attributes (handling of Go/No-Go data) assumes that for each unit there is an unknown critical level, above which it will respond and below which it will not. In the present work we have observed that the maximum temperature of the pulse that caused the firing is sometimes less than the maximum temperature of some preceding pulse. This indicates that the temperature is not the only parameter even though it may be the major one.

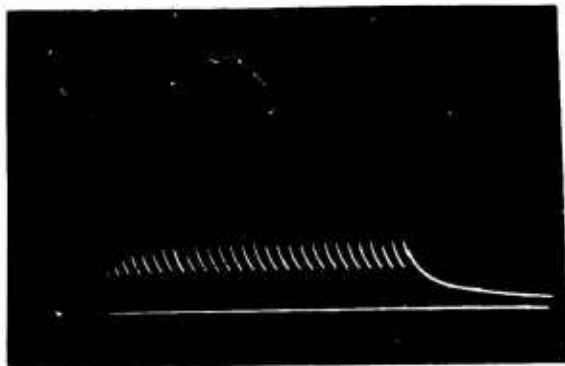
At a confidence of 95% we cannot demonstrate a difference between the first, second, and third radar exposures whether we treat the data as continuous or as Go/No-Go information. Also there may be no difference between the firing temperatures for DC and for microwave energy when we look at these grouped (averaged) results. On the other hand when we inspect individual data points and look at distributions of results, a different opinion can be formed.

Compared to the simulation firings a significantly lower bridgewire temperature is associated with the RF and, probably more important, the low end of the temperature range for the simulation firings are well defined while the lowest temperature radar firings seem to be scattered around within a 100° range.

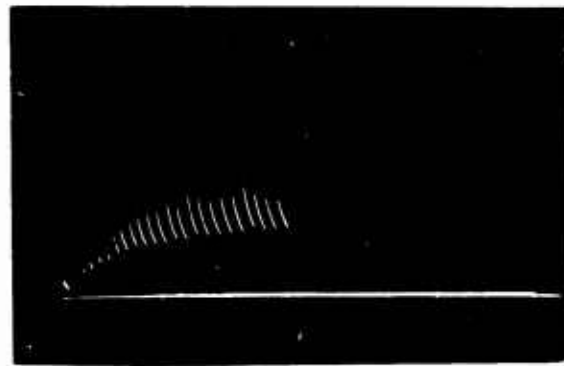
Graphical analysis uncovers no obvious connection between the temperature prior to firing and the thermal parameters associated with each squib. Although not shown, the squibs that fired did not differ as a group from the misfires. Numerical data, showing irradiation history, maximum bridgewire temperature and EED response are shown in Appendices B and C to permit comparison of these data with work which will be forthcoming.

The temperature history of three squibs is plotted by the bolder arrows in Figure 12. At the bottom of the chart, a squib is shown to have fired on the second exposure at 120° after having experienced a rise in bridgewire temperature of 120° on the first exposure. Even more unusual is the behavior of the unit which reached 210° on the first exposure, 240° on the second, and then proceeded to fire after having only reached 180° on the third irradiation. Another reached maximum temperatures of 210° and 180° on the first two exposures and then fired at a mere 130°C. One possible explanation may be that the explosive is being sensitized by the preceeding pulses. But we are not aware of any experimental evidence of sensitization by pre-pulsing.

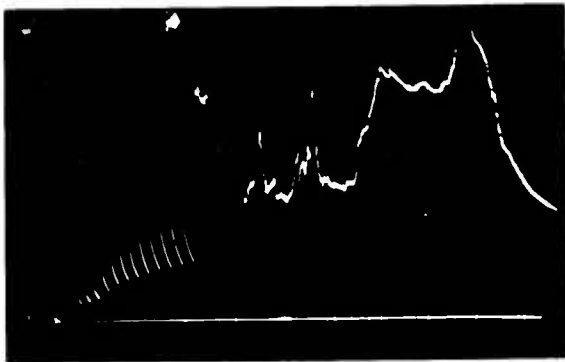
A typical oscilloscope trace of a squib that went through the normal thermal stacking to equilibrium cycling process and did not fire is shown in Figure 13a. The trace of a squib that did fire is shown in Figure 13b. The little spot immediately after the 24th pulse is where the highest temperature was detected. Sometimes the bridgewire did not burn out upon firing. A trace similar to that shown in Figure 13c results.



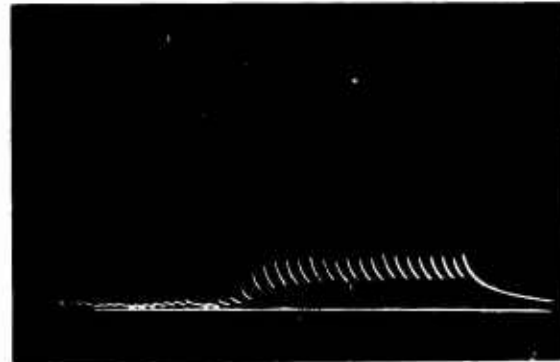
(a)



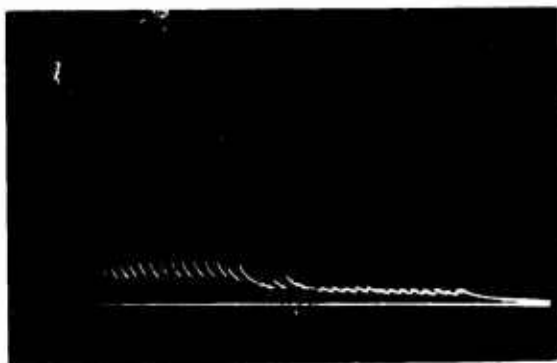
(b)



(c)



(d)



(e)

SWEEP 10 MS/CM
AMPLIFICATION 5 MV/CM

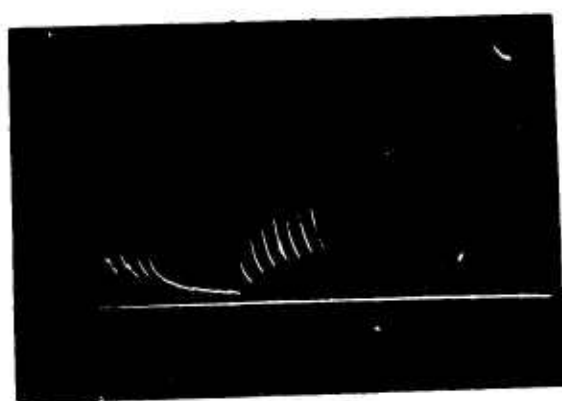
FIG. 13 VARIOUS OSCILLOGRAMS SHOWING NORMAL AND ANOMALOUS RESPONSES

Not all the squibs were as well behaved as these first few examples. Figures 13d and 13e illustrate a phenomenon whose cause cannot be pinpointed but might be due to corona discharge at the ends of the leads. The effect is to rob power from the bridgewire. A few squibs that exhibited this phenomenon fired anyway. Examples are shown in Figures 14a and 14b. Figure 14b is interesting in yet another way. Note that the cooling curve after the last pulse was not interrupted until about a millisecond later. A similar behavior was observed in Figure 14c where firing took place midway between successive pulses. Note also that the equilibrium bridgewire temperature after the explosive decomposed is apparently higher than before firing. The value of γ , the heat-loss factor, would be expected to be lower under these conditions. In Figure 14d the squib appears to have fired after the radar was turned off. It is tempting to ascribe such delays in thermal feedback after the last pulse to a cooking off of the explosive. However, some work which is yet to be published indicates that the time lag between application of an adiabatic pulse and thermal feedback may vary from 50 to 420 μ seconds. How much greater this time lag can be is not known.

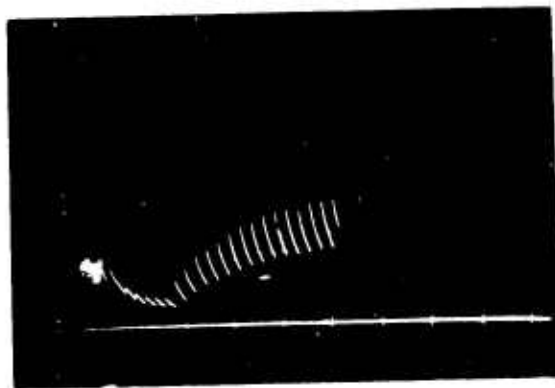
Another curious behavior pattern was that instead of the temperature remaining in a stable repetitive cycling pattern after the thermal stacking phase was over, some squibs experienced fluctuating temperature trends. Figure 13 b is an example. Figure 14c illustrates a squib that reached an equilibrium then suddenly rose to about twice that temperature for three pulses and fired. Approximately one-third of the squibs tested on the radar exhibited some sort of unpredictable behavior such as those described above. (There was no correlation between the characteristics of these squibs and the majority of squibs that showed normal thermal stacking.) The need for more study in this area is clearly indicated.

At this time, there is good evidence of two general mechanisms that may be responsible for the observed low temperature radar firing. In NOLTR 62-77 reference was made to standing wave ratio tests which proved that RF power was being absorbed other than in the bridgewire. This led to the conclusion that heating within the explosive itself could be taking place.

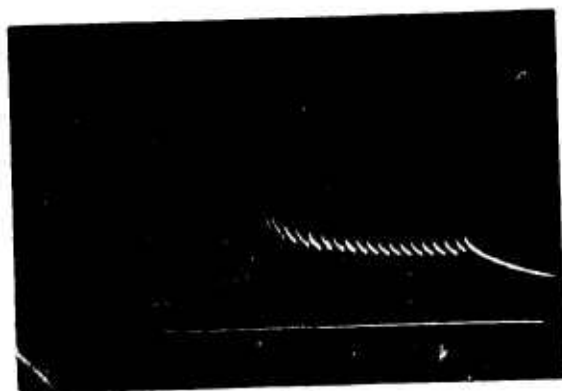
The likelihood of RF absorption by the explosive still exists. It was mentioned earlier that squibs modified by removal of cup and base charge showed an occurrence of firing and bridgewire temperatures similar to that of the fully loaded units. This may eliminate the cup and base charge as



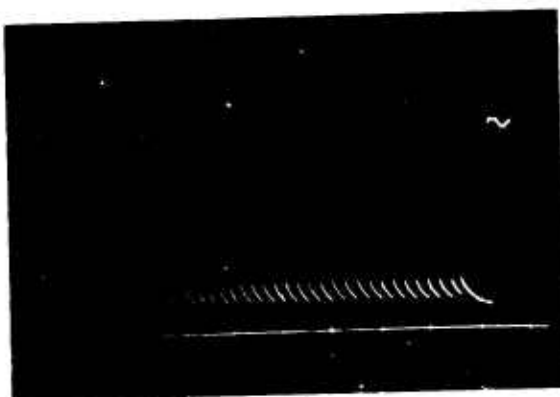
(a)



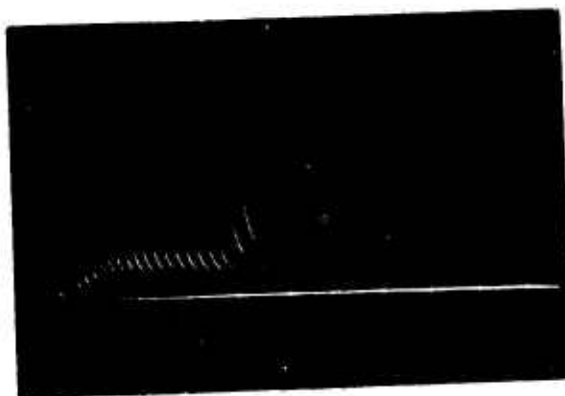
(b)



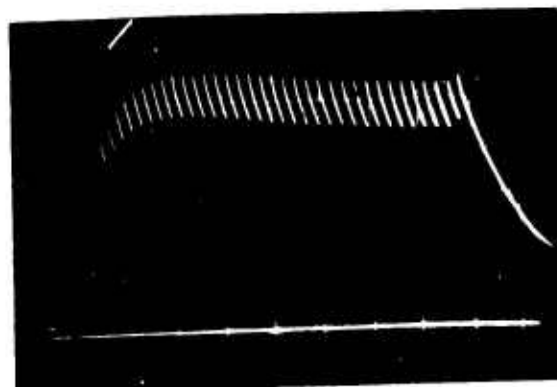
(c)



(d)



(e)



(f)

FIG. 14 VARIOUS OSCILLOGRAMS SHOWING NORMAL AND ANOMALOUS RESPONSE

agents in this mode of initiation. In addition, it was observed that after a squib fired, whether it was a fully loaded or a modified unit, if it were subjected to another burst of RF, the temperatures reached by the bridgewire would be much higher. Figure 14f is an oscillogram of the same squib shown in Figure 14e exposed to another burst of radar after it fired. This could be attributed to more power available to the bridge because the explosive is no longer there to absorb power.

Other evidence of RF heating in the explosive, specifically in the primary charge, is that the modified squibs were observed to fire with a dull sound as opposed to the sharp crack heard when they are fired by a surge of DC current.

Another possible contributing factor in low temperature RF firings is the skin effect. The skin depth for the bridgewire at 9Gc is about 0.1 mil. (See Appendix D) This means that about 90% of all heating is taking place within the outer 20% of the cross-sectional area. The present method of monitoring the bridgewire temperature necessarily results in average temperature figures. Hence, during each pulse the temperature at the surface of the bridgewire may be much higher than the value obtained by the monitoring process.

If the skin effect is the major factor, the mathematical model may not be at fault. Calculations similar to those in Appendix D indicate that present temperature monitoring techniques might show unusually low temperature firings at frequencies above approximately 200 megacycles. This is when the skin depth would equal the radius of the bridgewire. (There are various time constants connected with the heat flow in the wire and in the explosive, and there is a problem of relative distances - distance to the center of the wire vs minimum radius of a hot spot - which are involved. The problem is beyond simple calculations.)

The results of the present study support the data obtained two years ago from firings inside a wave-guide. But because the radiated energy environment more closely approaches practical conditions, the entire problem assumes a more immediate concern. Present simulators and other equipment used to detect bridgewire heating may not be adequate safety monitors in a radar field. The exact mechanism(s) of firings by radar is yet to be understood.

The many questions illustrate a need for more basic research into initiation by other than adiabatic conditions. It is now suspected that slow, almost bulk heating of the explosive, results in initiation by lower than expected (from an adiabatic standpoint) temperatures at the bridgewire. Hence, the important criterion in radar firings may not be the instantaneous bridgewire temperature but some measure of the temperature-time relationship as it relates to the reaction kinetics of the sensitive explosive surrounding the bridgewire.

To interpret accurately the results herein from a theoretical standpoint, further investigation into thermal stacking must be carried on. For example, data on time at firing versus energy per pulse, pulse height, pulse duration, etc. is needed. However, it is felt that this by no means will completely explain the low temperature firings reported on in this study. There is clear indication that the high frequency electromagnetic signal itself is responsible for some anomalous mode of initiation. The point is that this behavior must be isolated from what should be expected from thermal stacking by pulsing.

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APPENDIX A

THEORY OF POWER ABSORPTION IN FREE
SPACE BY THE SQUIB

When a radiated electromagnetic field impinges on a conductor, some of the electrons in the conductor are set in motion. The varying field causes similar variations in current in the conductor. An antenna is a conductor specially designed to intercept electromagnetic energy. It is constructed so that the fields produced by the currents in the conductors add in some direction instead of cancelling out.

A half or multiple half wavelength dipole is one type of antenna. It consists of two lengths of wire each some odd multiple of a quarter wavelength long (at the operating frequency) spread end to end and connected by a load at the center. The currents in the conductors are maximum at the load and zero at the outside ends while voltage is minimum at the center and maximum at the ends. The current and voltage distribution along the antenna will always be the same but their amplitudes will vary with the frequency of the incoming radiation.

Consider the three halves wavelength dipole antenna diagrammatically illustrated in Figure 2. At an arbitrary instant current flowing to the right is represented by a positive amplitude on the current distribution curve and current to the left by a negative amplitude. Similarly, voltages at any point are positive or negative according to the position of the voltage distribution curve above or below the antenna. (This configuration reverses during the next half wavelength.) The current and voltage distribution curves behave as standing waves on the antenna. Note that maximum current flows in the center. The load is therefore in a favorable position to dissipate maximum power by ohmic heating.

The squibs used in this study were prepared to approximate a three-halves wavelength antenna. The individual squib leads were cut to 2.2 centimeters so that they measured, when spread apart, 4.5 centimeters end to end rather than the 5.0 centimeters that would be expected from the free space wavelength for this radar of 3.33 centimeters.

The method used to monitor the bridgewire temperature requires that a constant small current flow through the bridgewire. Certainly the connections for this current must be somewhere on the leads of the squib. However, a serious reduction in power absorbed by a test squib (as evidenced by the fact that the bridgewire no longer glowed) was noted except when the wires for the monitoring current were carefully soldered 6.5 millimeters in from the ends of the leads. They then act as Lecher wires. Neither the Lecher wire length nor the manner in which connection is made was found to be critical.

This behavior is explained in Figure 2. One quarter wavelength in from the ends of the antenna are stationary voltage zero points - or nodes. This is where the DC monitoring current connections are made on the squibs. Any high impedance circuit connected to these nodes will not interfere with the standing wave voltage distribution and therefore will not disturb the functioning of the antenna or the quantity of power absorbed in the lead. The presence of the voltage nodes on the three halves wavelength antenna and not on the one half wavelength antenna is the reason for choosing the larger configuration. The smaller size would have actually been more favorable to work with in the confines of the end of the small horn.

The reader may find small discrepancies between the ideal situation and our experimentally observed distances. In practice an antenna is never perfectly isolated from surrounding objects which may have an effect upon the effective length of the antenna. Also, the wavelengths of electromagnetic waves are shorter in a conductor than they are in air. To further complicate the problem, there is what may be called an effective length associated with the wires molded into the plug body which connects the external lead wires. Also the antenna behavior is much more complex if the lead is reactive rather than purely resistance as has been assumed.

As a final comment, no attempt has been made to investigate the impedance matching between various parts of the antenna-like squibs. Perhaps this is an area for further study.

APPENDIX B

BRIDGEWIRE TEMPERATURE AND EED RESPONSE TO
PULSE BURSTS OF 9GC RADIATION

Unit I.D. Number	M ohms/°C	Number of Pulses			Temp.in Hundreds of °C above amb.			Notes
		First Exp.	Second Exp.	Third Exp.	First Exp.	Second Exp.	Third Exp.	
38	930	20	19*		1.3	1.5*		*indicates firing
93	955	20	20	20	1.3	1.0	1.4	
33	985	20	20	20	1.4	1.4	1.5	
48	900	6*			3.2*			
92	963	20	20	20	1.4	1.0	1.4	
74	954	9*			2.5*			~indicates lead wire snapped off
9	963	20	20	~	1.7	1.4	~	
54	1017	20	20	20	1.7	1.5	1.8	
29	1158	11*			2.8*			
24	934	20	20	20	1.2	1.2	1.3	
100	903	20			0.8	1.8*		To express temperature in °K, multi- ply by 100 and add to 300
56	882	20	20	20	1.1	1.0	0.7	
64	859	20	20	20	1.6	1.7	1.7	
22	904	20	20	20	1.7	1.8	1.8	
63	864	20	20	20	1.7	1.7	2.3	
45	990	20	20	20	1.6	1.5	1.5	
34	972	20	20	8*	1.7	1.4	2.4*	
59	990	20	20	20	1.1	1.7	2.0	
71	1006	20	20	20	1.1	1.6	2.1	
75	897	20	20	20	1.8	1.8	2.1	
26	972	20	20	20	1.5	2.1	0.6	
42	996	20	20	20	1.1	2.0	2.0	
19	940				1.5*			
55	1020	40	40	29*	2.5	2.3	2.9*	
67	1047	40	40	17*	1.9	1.8	2.6*	
CONTINUED								

NOLTR 64-117

Number	M μohms/°C	Number of Pulses			Temp. in Hundreds of °C above amb.			Notes
		First Exp.	Second Exp.	Third Exp.	First Exp.	Second Exp.	Third Exp.	
96	954	7*			2.5*			*indicates firing
58	933	40	40	40	1.3	1.3	1.6	
41	914	7*			2.2*			
13	845	21*			2.5*			
60	990	6*			2.0*			
37	898	40	40	40	1.3	1.5	1.5	
16	969	35*			1.5*			
23	955	17*			2.2*			
88	900	40	40	22*	2.1	1.8	1.4*	
47	894	7*			2.5*			
72	1003	40	8*		2.0	3.2*		
66	992	40	40	40	1.9	1.9	2.2	
27	883	40	40	19*	2.1	2.4	1.8*	
35	889	40	40	40	1.3	1.4	1.7	
36	961	38*			1.4*			
11	985	9*			2.4*			~indicates lead wire snapped off
68	942	15*			2.4*			
90	911	40	40	40	1.5	1.5	1.5	
31	963	40	40	~	1.3	1.7	~	
82	1043	40	40	40	1.6	2.2	2.0	
79	915	40	40	40	1.5	1.1	1.2	
2	1022	5*			2.0*			
25	896	40	40	40	2.1	2.0	1.4	
39	931	11*			2.6*			
1	939	40	8*		1.2	1.2*		
40	961	40	7*		1.7	3.1*		
5	916	3*			1.9*			
78	960	40	9*		1.8	2.7*		
89	942	40	40	40	2.0	1.6	2.0	
51	977	40	40	40	1.0	1.0	1.7	

CONTINUED

Number	M μ ohms/ $^{\circ}$ C	Number of Pulses			Temp. in Hundreds of $^{\circ}$ C above amb.			Notes
		First Exp	Second Exp.	Third Exp.	First Exp.	Second Exp.	Third Exp.	
14	1195	40	40	40	1.2	1.0	1.0	*indicates firing
77	987	21*			3.0*			
20	1068	24*			2.6*			
50	1216	5*			2.3*			
80	957	16*			2.6*			
85	904	40	40	40	1.4	1.4	1.4	
43	937	16*			2.7*			
57	944	40	40	40	1.6	1.3	1.6	
10	875	40	40	40	1.1	1.3	1.1	
15	974	27*			2.6*			
81	941	40	40	40	1.9	1.5	0.5	
28	997	6*			2.5*			
76	902	40	40	40	1.2	1.4	0.8	

APPENDIX C

NOLTR 64-117
SHEETBridgewire Temperature and EED Response to a DC Simulation of a Train
of 9Gc Pulses

Unit I.D. Number	M micro- ohms/°C	Number of Pulses	Temperature Hundreds of °C	Current Ampli- tude	Response
52	960	14	3.2	1.8	x
12	975	14	2.7	1.8	x
94	1024	14	2.7	1.8	x
95	923	14	2.7	1.8	x
65	1115	12	2.8	1.8	x
86	882	15	3.5	1.8	x
49	1216	14	3.1	1.8	x
53	982	11	3.1	1.8	x
6	849	12	2.3	1.8	x
91	993	11	2.6	1.8	x
97	959	19	3.0	1.8	x
61	945	11	2.7	1.8	x
17	976	14	2.9	1.8	x
69	932	11	3.0	1.8	x
21	1021	11	2.5	1.8	x
62	820	10	3.2	1.8	x
4	1070	13	2.6	1.8	x
84	1089	12	2.8	1.8	x
99	925	10	2.8	1.8	x
3	1005	9	3.1	1.8	x
18	978	20	2.3	1.5	o
7	977	20	2.2	1.5	o
8	901	20	2.3	1.5	o
46	949	20	2.5	1.5	o
83	888	7		2.0	x
44	935	?	?	2.0	x
87	922	?	?	2.0	x
70	881	7	3.7	2.0	x
73	994	8	3.6	2.0	x
KEY: x indicates EED fired					
o indicates EED did not fire					
? indicates loss of photographed data					

APPENDIX D

SKIN DEPTH CALCULATIONS

The skin depth for a cylindrical conductor is approximated by:

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

where ω = frequency

μ_0 = permeability of free space

σ = conductivity of the wire.

In the mks system,

$\omega = 2\pi \times \text{frequency in cps}$

$\mu_0 = 4\pi \times 10^{-7}$

$\sigma = 3.3 \times 10^6$ mhos/meter (80-20 platinum-iridium)

$\therefore \delta \approx 3 \times 10^{-6}$ meters = 1×10^{-4} inches = .1 mil.

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14	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Squibs - Mk 1 Mod 0 Squibs - radar firing Squibs - sensitivity Electroexplosive devices - sensitivity HERO - radar firing						

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