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Development of the MC3133 Reefing Line Cutter

James R. Craig

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DEVELOPMENT OF THE MC3133 REEFING LINE CUTTER

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ABSTRACT

A pyrotechnic actuated reefing line cutter has been developed which, in response to an incoming programmable time delayed electrical firing signal, severs a nylon or Kevlar parachute reefing line following parachute deployment. This report describes the design objectives and final design concept which evolved. First order approximations and parameter studies leading to a preprototype design are presented. Significant evaluation studies that resulted in the selection of boron/calcium chromate for the initiating charge and titanium subhydride/potassium perchlorate for the output charge are discussed in detail. Final design verification testing data show that the reefing line cutter will meet functional requirements after the following sequential environments: thermal shock, -54° C to 90° C; mechanical shock, 9806 m/s^2, 2 ms duration; vibration, 98 m/s^2, 26-2000 Hz; and linear acceleration, 1960 m/s^2 for two minutes.

ACKNOWLEDGMENT

The author acknowledges the contribution of F. J. Villa of Sandia Laboratories and Clyde Jones of Unidynamics Phoenix, Incorporated, who provided valuable assistance in the development work described.

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SUMMARY

The objective of the program was to develop a pyrotechnic actuated reefing line cutter which, in response to an electrical firing signal, will sever the nylon or Kevlar reefing line of a parachute. Present reefing line cutter systems use either a pyrotechnic or an electrical delay that is an integral part of the cutter assembly. For this application, a programmable time delayed firing signal is provided by means of an interconnecting cable that is attached to one of the shroud lines of the parachute and terminates in a molded plastic connector that is attached to the cutter assembly.

The design which evolved and is the basis for this report is designated the MC3133 Reefing Line Cutter. Development test data show that the MC3133 is more than adequately designed to reliably perform its function of severing either a nylon or Kevlar cord; the cords have a tensile strength of 54 kN and 60 kN, respectively. The pyrotechnic material which provides the energy required to sever the reefing line is a 33/67 mixture of $TiH_{.65}/KC1O_4$ and has a charge weight of 84 mg; the charge weight at which failure to sever the kevlar line occurs is below 50 mg. A 20/80 mixture of $B/CaCrO_4$ is used to achieve reliable ignition sensitivity to a 5.0 ampere, 7.5 ms firing pulse. This material has a thermal coefficient of expansion which closely matches that of the ceramic header charge holder. Also, the powder is not electrically conductive. A change in bridgewire resistance as a function of temperature is therefore minimal.

Extensive evaluation of the high voltage or electrostatic breakdown characteristics of the header assembly in which the pyrotechnic charge materials are contained shows that the spark gap and voltage breakdown paths external to the pyrotechnics provide good protection for preventing initiation of the cutter actuator by means of high voltage-electrostatic discharge pulses.

Final design verification testing shows that the MC3133 Reefing Line Cutter will reliably perform its function over a temperature range of -62° C to 90° C after experiencing sequential environments of mechanical shock, vibration, and linear acceleration.

DEVELOPMENT OF THE MC3133 REEFING LINE CUTTER

I. Introduction

The MC3133 is a pyrotechnic actuated reefing line cutter which, in response to an electrical firing signal, severs the reefing line of a parachute. The dereefing occurs after a preset time interval following parachute deployment. Present reefing line cutter systems use either a pyrotechnic or an electronic delay that is an integral part of the cutter assembly. For this application, a programmable time delayed firing signal to the reefing line cutter is provided by means of an interconnecting cable that is attached to one of the shroud lines of the parachute.

Design definition of the MC3133 is in accordance with the drawing listed on PX315965. Development was successfully concluded in May 1977.

II. Design Objectives

The general characteristics which were used as design objectives for development of the reefing line cutter are summarized in Table I.

TABLE I

Characteristics and Design Objectives for Reefing Line Cutter Development

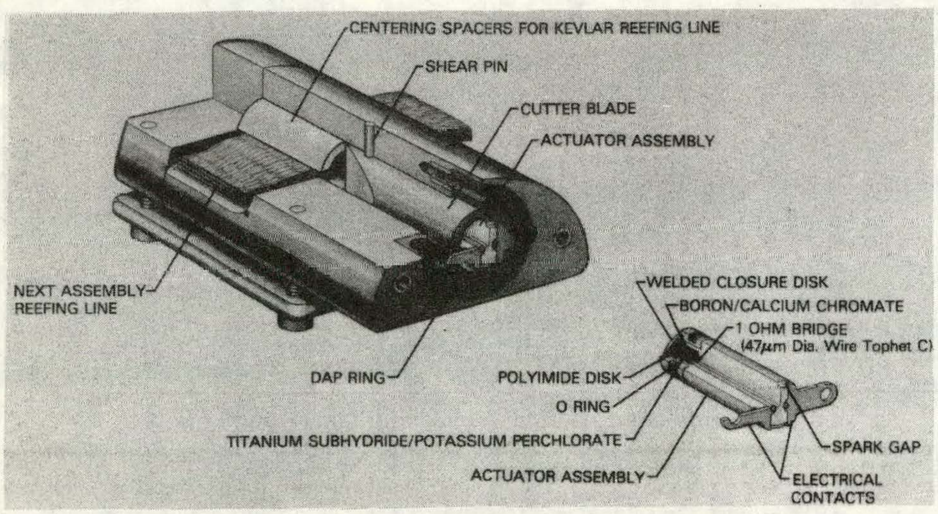
Characteristics	Design Objectives
Size	Semicylindrical configuration, width and length not to exceed 60 mm by 127 mm, respectively.
Electrical cable termination	Two conductors (shielded termination) to be retained by the end cap of the reefing line cutter or by the connector.
Actuator	A hermetically sealed pyrotechnic actuator that will nest within the shank portion of the cutter blade.
Cutter blade retention	The use of a shear pin to hold the cutter blade in place while providing a means of optimizing blade velocity and impact energy after reefing line actuation.
Actuator no-fire current	One ampere through a one-ohm bridgewire for 5 minutes.
Actuator all-fire current	Must reliably initiate, given 5.0 amperes for 7.5 ms.
Electrostatic discharge susceptibility	Provide a spark breakdown path in the actuator header subassembly that is external to the bridgewire pyrotechnic interface. The actuator shall not initiate, given a discharge pulse from a 600-pF capacitor charge to 20 kV and in series with a 500-ohm resistor.

TABLE I (cont)

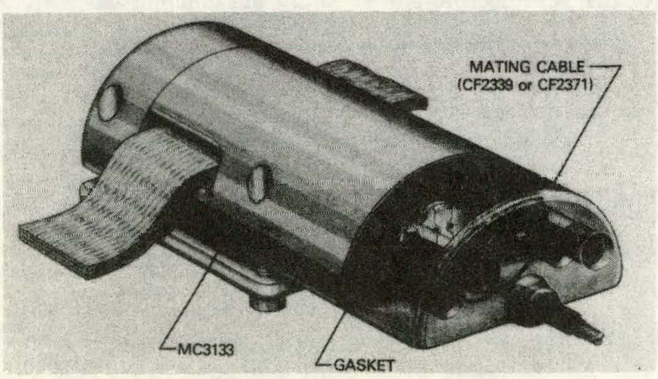
Characteristics	Design Objectives
Output	1. Capable of severing Kevlar type 29 cord treated with a 15% solution of polyvinyl butyrate and Sergene. Minimum tensile strength of the cord is 60 kN. 2. Capable of severing nylon cord per MIL-W-4088. Minimum tensile strength of the cord is 53 kN.
Environmental:	
Temperature	-54° C to 90° C
Sine vibration	98 m/s^2, 26 to 2000 Hz
Mechanical shock	9806 m/s^2, 1.5 to 2 ms duration (half sine shape)
Acceleration	1960 m/s^2, 2 minutes

III. Design Concept

The design concept for the reefing line cutter is shown in Figure 1. Two cutters are mounted to the parachute skirt band and suspension line by means of a base plate and four mounting screws.



a. MC3133 Reefing Line Cutter



b. MC3133 Reefing Line Cutter and Cable Assembly

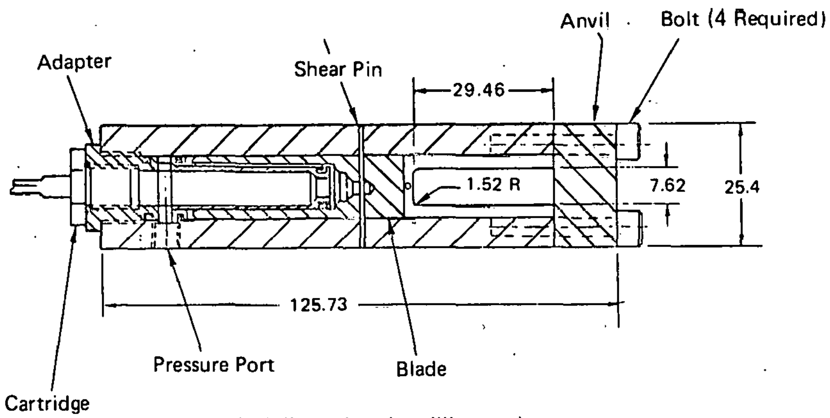
Figure 1. MC3133 Reefing Line Cutter and Cable Assembly

The cutter functions when a programmable time delayed firing signal is provided through a shielded twin lead interconnecting cable that is attached to one of the parachute shroud lines. This cable terminates in a molded plastic connector which has two bushings through which screws are inserted for attachment and electrical connection to tabs that are part of the pyrotechnic actuator bridgewire circuit. A molded plastic ring provides electrical isolation from the aluminum-chromium coated housing of the cutter. The pyrotechnic train in the actuator consists of an initiating charge of 12 mg of 20/80 boron/calcium chromate ($B/CaCrO_4$) and an output charge of 86 mg of titanium subhydride/potassium perchlorate ($TiH_{.65}/KClO_4$). The bridgewire is a nickel chromium alloy having a diameter of 47 μm. The nominal length between the bridgewire weld nuggets is 1.55 mm, which provides a nominal bridgewire resistance of one ohm. The cutter blade is of Ketos tool steel, oil quenched and heat treated for a Rockwell hardness of C52-56. The cutting edge has a 50° included angle and is cadmium plated. The blade has a 9.52-mm diameter cavity in which the actuator assembly with an O-ring is inserted. A shear pin is used to hold the blade in the cutter housing. When a Kevlar cord is to be severed, two teflon inserts having a semicircular configuration are inserted into the housing of the cutter assembly for positioning the cord to the horizontal centerline of the blade. These inserts are not required when severing the nylon cord, which has a much larger cross section. After receiving a firing signal, the pyrotechnic actuator provides the energy necessary to shear the shear pin. At this time, the cutter blade is released and accelerated through the reefing line bore, severing the cord. An anvil plate adsorbs the impact of the blade. The average stroke time is 550 μs.

IV. Heavy Wall Preprototype Reefing Line Test Cutter

First Order Approximations

Initial effort in the development program was the designing of a heavy wall preprototype cutter for design evaluation studies. The first test cutter configuration had a provision for measurement of the propellant pressure-time profile in the actuator. The test cutter configuration is shown in Figure 2.



(All dimensions in millimeters)

Figure 2. Preprototype Test Cutter

Propellant charge sizing was established by using a calculated weight of 24.83 gm for the cutter blade (which was later determined to be 19.32 gm) and a desired stroke time of 10 ms.

The acceleration required is:

$$a = \frac{2x}{t^2} = \frac{2(3.175\ \text{cm})}{(0.01\ \text{S})2} = 63{,}500\ \text{cm/s}^2$$

The force on the blade needed to produce this acceleration is:

$$F = \frac{W}{9}\,\alpha = \frac{24.83\ \text{gm}\ (63{,}500\ \text{cm/s}^2)}{980\ \text{cm/s}^2}$$

$$= 1{,}609\ \text{gm} = 15.78\ \text{N} \quad .$$

Several static tests established an estimated force of 2224 N for cutting a 54 kN nylon test cord. The total estimated force is:

$$F_t = 2{,}224\ \text{N} + 15.78\ \text{N} = 2{,}240\ \text{N or } 228\ \text{kg} \quad .$$

The total energy required is:

$$E = F_{\Delta x} = 228\ (3.18\ \text{cm}) = 725\ \text{kg-cm}\ .$$

The charge weight of the propellant is:

$$C = \frac{E}{NRT_n} = \frac{725\ \text{kg-cm}}{(13{,}377\ \text{kg-cm})\ 0.8} = 0.068\ \text{gm} \quad .$$

The assumed value of efficiency, n, for the NRT of Hi-Temp is 0.8.

The internal pressure required in the cutter to provide the 3340 N blade severing force is:

$$P = \frac{F}{A} = \frac{2240}{71 \times 10^{-6}\ \text{m}^2} = 31.5\ \text{MPa} \quad .$$

Due to the added 1.77 cc free volume of the pressure transducer, an additional propellant charge load of 32 mg was included, giving a total propellant load of 100 mg.

In considering the initial shear pin design, a pin diameter of 1.575 mm was chosen. This provides an area of 1.936 mm^2 or 1.936×10^{-6} m^2. The pin in double shear should fail at a pressure of 31.5 MPa or 2240 N. The required material strength of the pin is:

$$\frac{2240 \text{ N}}{2(1.936 \times 10^{-6} \text{ m}^2)} = 579 \text{ MPa} .$$

Using the equation $\sigma_s = 0.9\ \sigma\mu$, the ultimate material yield strength is σ_γ 643 MPa. After reviewing material properties in this range, annealed stainless steel alloy 303 was selected.

Propellant Charge Tests

Initial evaluation of the preprototype reefing line cutter performance was made for varying Hi-Temp propellant charge weights of 80 mg to 120 mg. A pyrotechnic initiator charge material of 40 mg of 50/50 $B/CaCrO_4$ was arbitrarily selected as being capable of igniting the propellant. The data from this series of tests are presented in Table II. Cutter performance plotted as either a reefing line severance or no severance as a function of propellant charge weight is shown in Figure 3. The corresponding peak pressures obtained are shown in Figure 4. From these data it was apparent that for test cutter configuration, shear pin material, and diameter used, a minimum of 120 mg of Hi-Temp is required to sever the 54 kN nylon cord.

A block diagram of the test instrumentation used during initial cutter evaluation testing is shown in Figure 5. The test setup used for the cutter is shown in Figure 6.

Shear Pin Material and Diameter Determination

The preceding propellant charge weight evaluation tests showed that complete severing of the nylon cord occurred only for charge weights greater than 100 mg. It was apparent that in order to reduce the output charge weight, a reduction in the diameter of the shear pin should be made. Before proceeding in this direction, alternate shear pin materials were evaluated. The materials selected were:

1. 80-20 annealed nickel-chromium resistance wire,
2. 7075-T6 aluminum, and
3. 360 annealed brass.

The shear pin material tests are summarized in Table III. It was concluded that 20-80 nickel-chromium (Nichrome V) wire would provide the most consistent shear pin failure. As shown in the data analysis of Table IV, there is a significant difference in the calculated dynamic fail level as compared to the static failure level.

Upon completion of the initial shear pin study, a series of tests were conducted to determine the feasibility of replacing the Hi-Temp propellant with a suitable pyrotechnic. Following this, a final determination of shear pin diameter was made for the prototype design.

TABLE II

Preprototype Cutter Performance for Various Hi-Temp Propellant Charge Loads

Date	Test No.	Cartridge S/N	Ignition Charge (mg)	Output Charge (mg)	Bridge Resistance (ohms)	Shear Pin Material	Ignition Time (ms)	First Pressure (ms)	Peak Pressure (MPa)	Time of Peak (ms)	Transfer Time (ms)	Pressure At Knee (MPa)	Cutter Performance*
10-8-75	1	6	40	100	0.99	303 CRES	1.7	4	35.8	5	--	--	No Cut
10-8-75	2	4	40	100	1.04	303 CRES	1.8	8	35.8	9	0.70	9.65	Cut
10-8-75	3	2	40	100	1.00	303 CRES	1.6	3	37.9	4	--	--	No Cut
10-9-75	4	9	40	100	1.00	303 CRES	1.8**	5	35.3	5	0.45	11.03	Cut
10-9-75	5	7	40	100	0.95	303 CRES	1.7	4	35.2	6	--	--	No Cut
10-10-75	6	8	40	100	0.94	303 CRES	1.7	2	35.3	3	0.56	11.03	Cut
10-11-75	7	13	40	80	0.95	303 CRES	1.8	3	28.3	4	--	--	No Cut
10-11-75	8	14	40	80	0.94	303 CRES	1.7	2	27.6	3	--	--	No Cut
10-11-75	9	21	40	80	0.94	303 CRES	1.8	3	27.6	5	--	--	No Cut
10-11-75	10	15	40	120	0.90	303 CRES	1.6	4	35.8	5	0.65	12.40	Cut
10-11-75	11	18	40	120	1.00	303 CRES	1.6	3	35.8	3	0.67	12.40	Cut
10-11-75	12	22	40	120	0.98	303 CRES	1.7	2	35.8	2	0.79	12.40	Cut

*All cuts were complete and acceptable. On the no cut shots the shear pin did not shear and the blade did not move.

**Visicorder data.

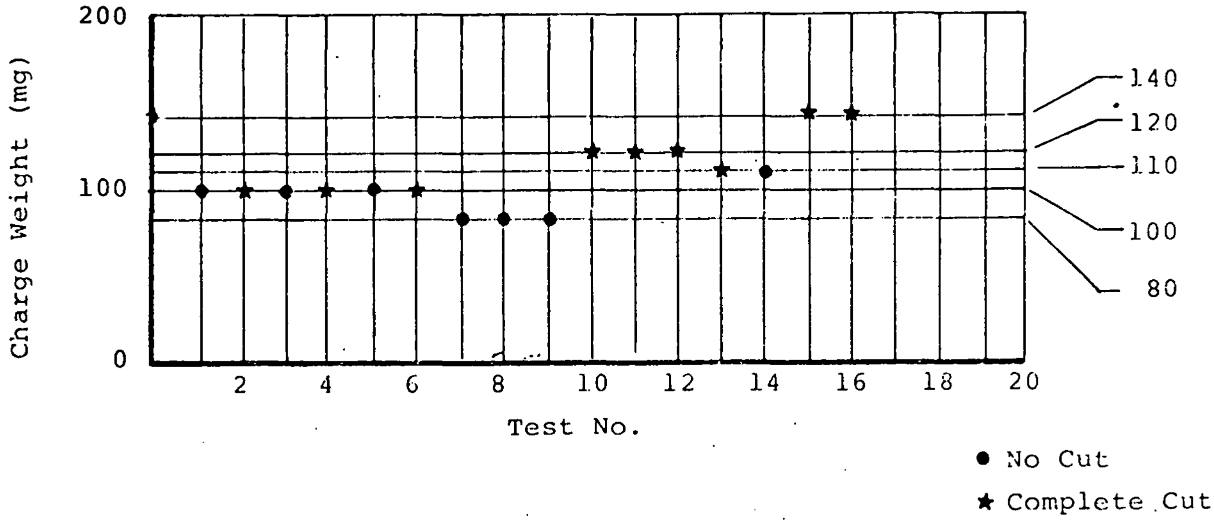


Figure 3. Preprototype Cutter, Reefing Line Cutting as a Function of Propellant Charge Weight

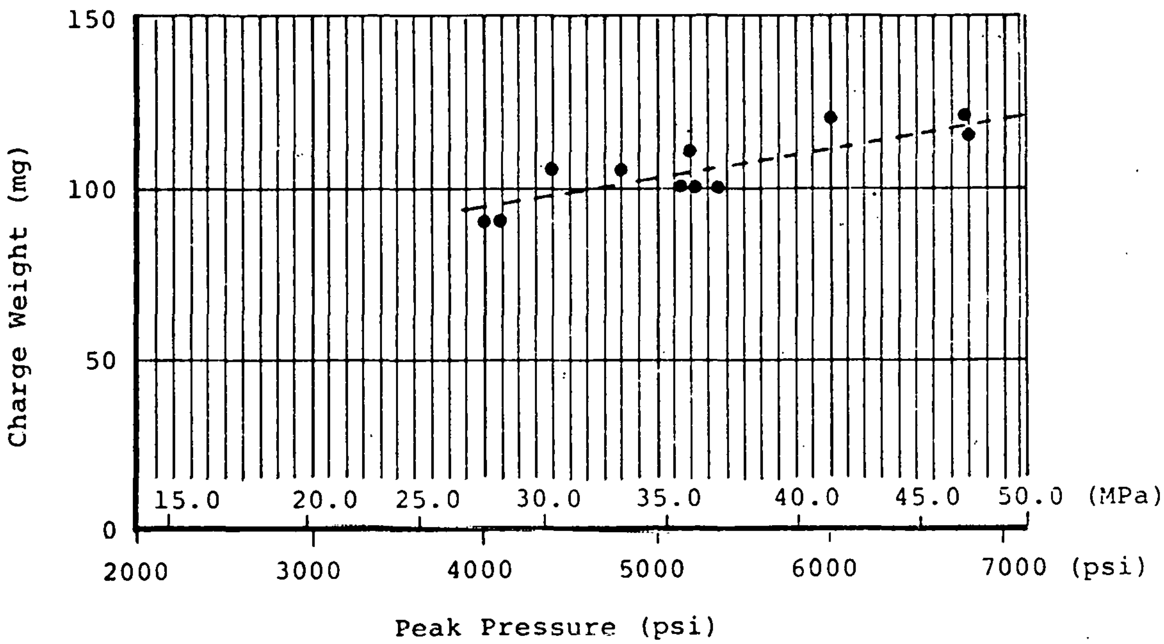


Figure 4. Preprototype Cutter, Peak Pressure as a Function of Propellant Charge Weight

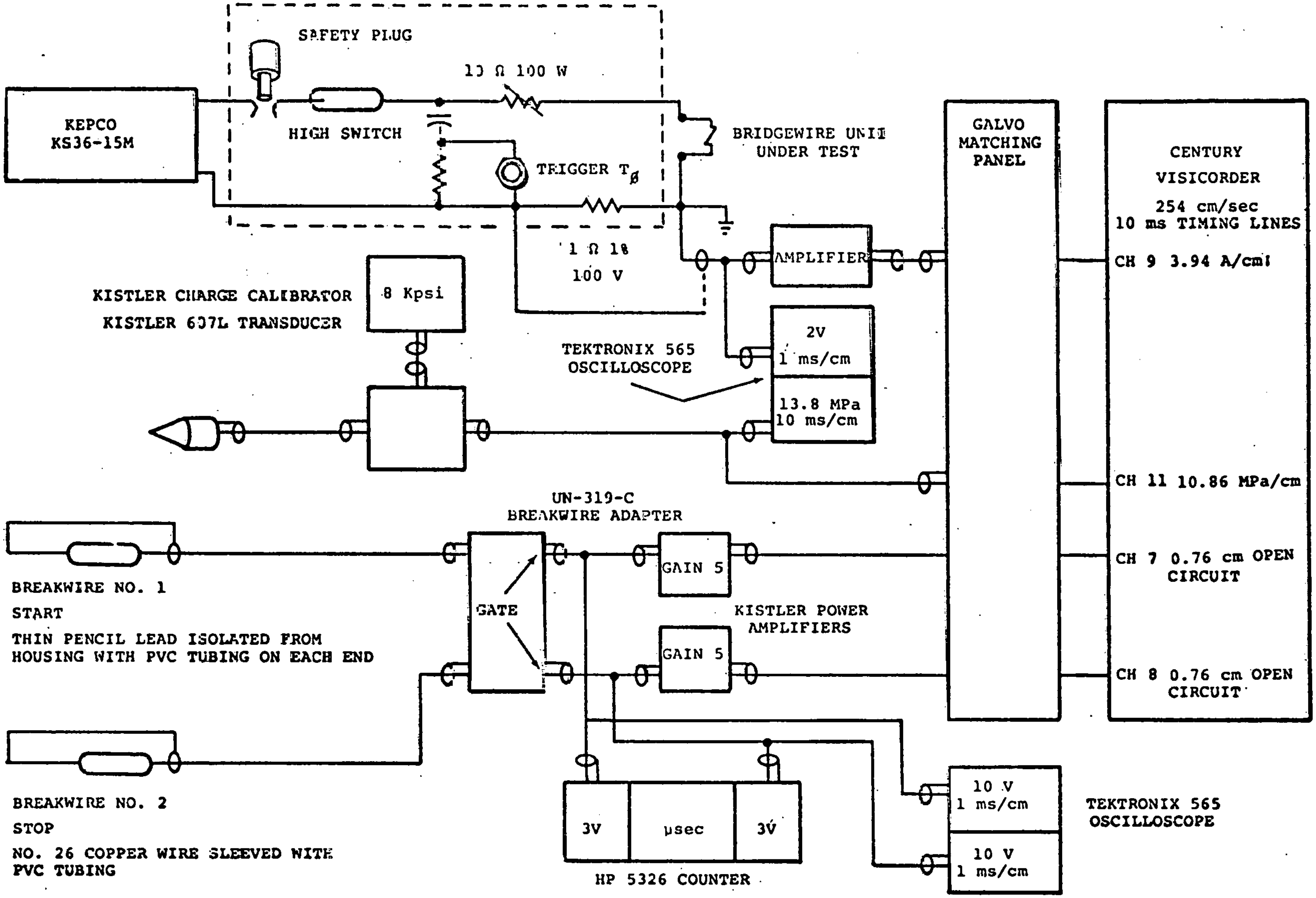


Figure 5. Block Diagram of Test Instrumentation

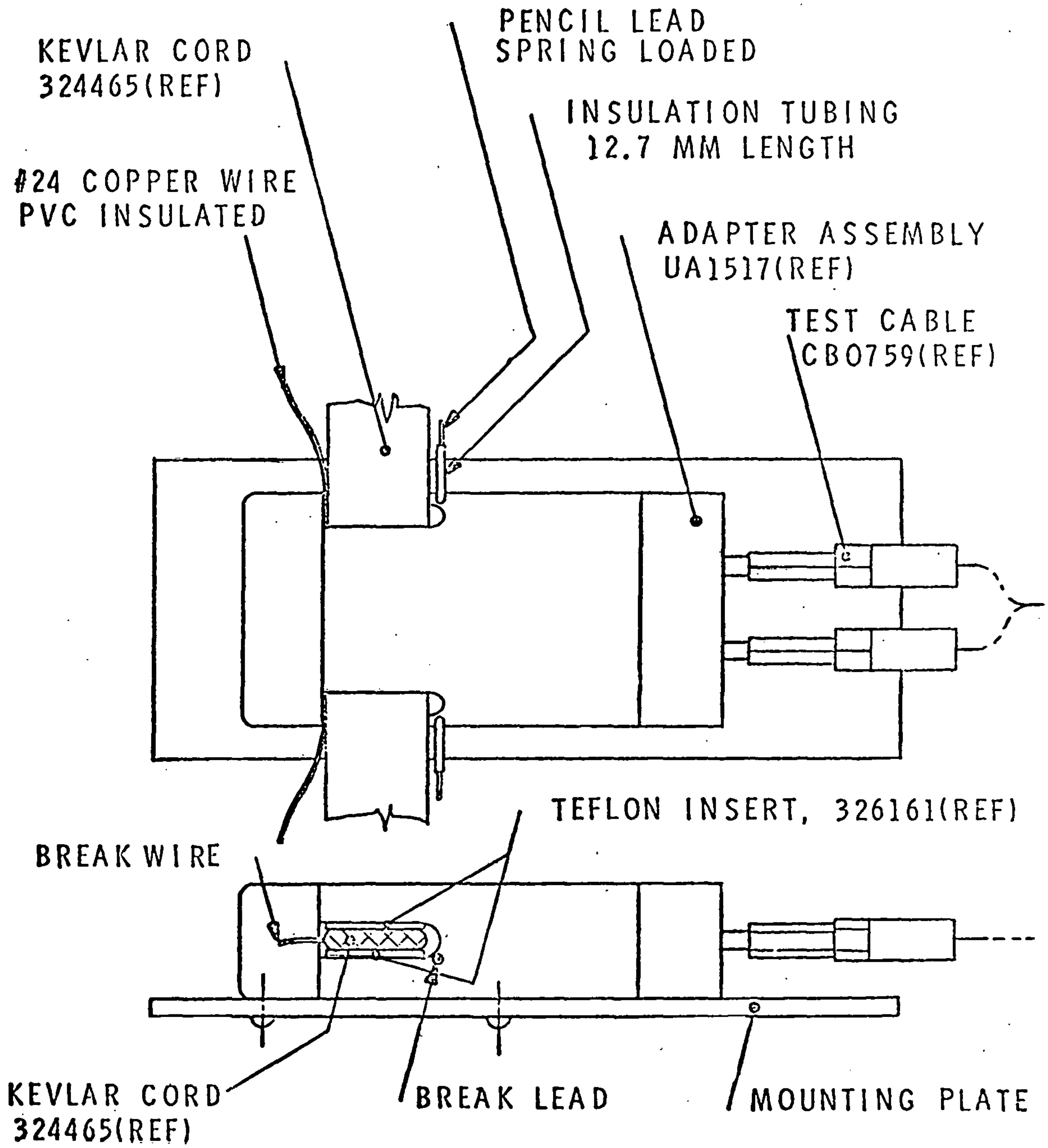


Figure 6. Cutter Test Setup

TABLE III

Shear Pin Tests, Preprototype Reefing Line Cutter

Date	Test No.	Cartridge S/N	Ignition Charge (mg)	Output Charge (mg)	Bridge Resistance (ohms)	Shear Pin Material	Ignition Time (ms)	First Pressure (ms)	Peak Pressure (MPa)	Time Of Peak (ms)	Transfer Time (ms)	Pressure At Knee (MPa)	Cutter Performance*
11-7-75	17	30	40	120	1.08	Brass	1.2	2.2	41.0	2.4	0.75	13.79	Cut
11-7-75	18	31	40	120	1.14	Brass	1.2	4.1	45.5	5.0	0.71	13.79	Cut
11-7-75	19	32	40	120	1.00	Brass	1.1	2.2	44.8	2.5	0.75	13.79	Cut
11-7-75	20	33	40	120	1.10	Brass	1.1	2.3	55.2	2.4	0.59	13.79	Cut
11-7-75	21	34	40	120	0.96	Aluminum	1.2	3.2	40.7	3.4	0.72	13.79	Cut
11-7-75	22	35	40	120	1.13	Aluminum	1.1	3.4	37.9	3.6	0.66	12.40	Cut
11-7-75	23	36	40	120	1.10	Aluminum	1.1	2.0	45.5	2.1	0.71	12.40	Cut
11-7-75	24	37	40	120	1.01	Aluminum	1.0	4.5	34.5	5.2	0.83	12.40	Cut
11-7-75	25	38	40	120	1.00	Nickel Chromium	1.1	2.4	41.7	2.5	0.73	12.40	Cut
11-7-75	26	39	40	120	1.10	Nickel Chromium	1.0	2.4	38.6	2.8	0.58	12.40	Cut
11-7-75	27	40	40	120	1.02	Nickel Chromium	1.1	3.2	41.7	3.4	0.78	13.79	Cut
11-7-75	28	41	40	120	1.21	Nickel Chromium	1.2	5.4	42.7	5.9	0.68	13.10	Cut

*All cuts were complete and acceptable. On the no cut shots the shear pin did not shear and the blade did not move.

TABLE IV

Shear Pin Data Analysis

Shear Pin Material	Test No.	Pressure At Failure (MPa) Scope (1)	Pressure At Failure (MPa) Visicorder (1)	Calculated Dynamic Failure (N)	Measured Static Failure (N)
360 Brass Annealed	17	41.0	36.4		
	18	45.5	40.0		
	19	44.8	37.5		
	20	55.2	41.4		
		Σ = 186.5	Σ = 155.3	F_{s_1s} = 3318 (2)	F_s = 1245
		$\bar{X}$ = 46.6	$\bar{X}$ = 38.8		
		S = 6.05	S = 2.28	F_{s_1V} = 2762 (3)	
7075-T6	21	40.7	35.9		
	22	37.9	36.1		
	23	45.5	42.2		
	24	34.5	35.8		
		Σ = 158.6	Σ = 150	F_{s_1s} = 2824	F_s = 1334
		$\bar{X}$ = 39.7	$\bar{X}$ = 37.5		
		S = 4.65	S = 3.14	F_{s_1V} = 2669	
80% NiCr Alloy Annealed	25	41.7	40.0		
	26	38.6	37.8		
	27	41.7	38.6		
	28	42.7	-		
		Σ = 164.7	Σ = 116.4	F_{s_1s} = 2668	F_s = 1824
		$\bar{X}$ = 41.2	$\bar{X}$ = 38.8		
		S = 1.78	S = 1.11	F_{s_1V} = 2762	

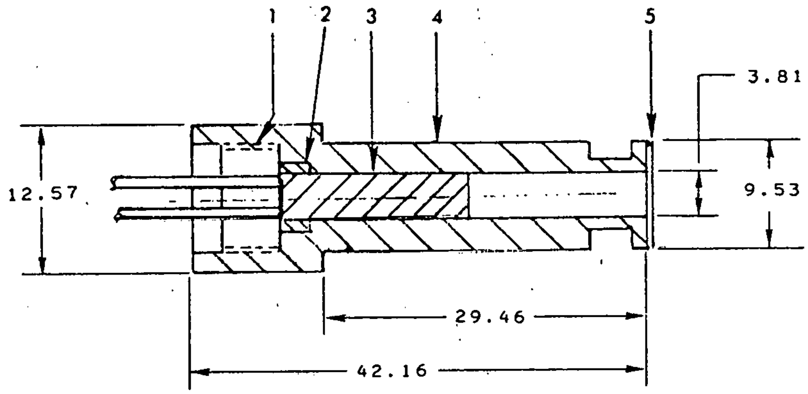
NOTES

(1) The oscilloscope was capable of picking up the very fast peak pressure profiles, while the visicorder was not.

(2) F_{s_1s} = Shear force in double shear calculated from oscilloscope data.

(3) F_{s_1V} = Shear force in double shear calculated from visicorder data.

The pyrotechnic material initially selected for evaluation as an output charge in the preprototype configuration was a 33/67 formulation of $Ti/KClO_4$. The test cutter configuration for this series of tests was revised. The pressure transducer port was eliminated, and changes were made to the actu ator. The configuration is shown in Figure 7. The data shown in Table V summarize the results obtained for preprototype cutters having various pyrotechnic or propellant charge loads. From these data it was concluded that a $Ti/KClO_4$ charge load of 120 mg would be adequate for the cutter.



(All dimensions in millimeters)

LEGEND
1 - P39210 HEADER
2 - INSULATOR
3 - PROPELLANT
4 - 304 STEEL HOUSING
5 - 0.076 MM 304 STEEL DISK

Figure 7. Modified Actuator for Preprototype Test Cutter

Final determination of the diameter of the NiCr shear pin for the prototype reefing line cutter was based on the following considerations.

1. The desired double shear level for the shear pin is 2224 N, which was the static failure level obtained during initial static testing of 54 kN nylon cord.

2. The average dynamic pressure at shear pin failure for the 1.575 mm diameter NiCr pin was 41.2 MPa.

3. The area of the cutter blade is 71.26 mm^2.

4. The shear strength of the NiCr pin was originally calculated to be 459 MPa. A corrected value, based on test results obtained, is:

$$41.2 \text{ MPa } (71.26 \text{ mm}^2) = 2936 \text{ N} .$$

The double shear area for the 1.575 mm diameter pin is 3.90 mm^2. Thus,

$$\sigma_s = \frac{2936 \text{ N}}{3.90 \text{ mm}^2} = 753 \text{ MPa} .$$

TABLE V

Summary of Performance for Preprototype Cutter Having Various Pyrotechnic and Propellant Charge Loads

Test	Output Material	Quantity (mg)	Consolidation Pressure (MPa)	Test Temperature	Ignition Time (ms)	Stroke (ms)	Cutter Performance	Anvil Condition
1	$Ti/KClO_4$ [1]	416	103	Ambient	1.25	0.476	Cut	Deep Cut
2	Hi-Temp [2]	86	13.78	Ambient	1.05	0.432	Cut	Deep Cut
3	Hi-Temp	65	13.78	Ambient	1.10	0.519	Cut	Deep Cut
4	$Ti/KClO_4$	234	103	Ambient	1.05	0.544	Cut	Deep Cut
5	Hi-Temp	50	13.78	Ambient	1.07	0.712	Cut	Nominal Cut
6	$Ti/KClO_4$ [3]	210	137.8	Ambient	1.38	0.470	Cut	Deep Cut
7	Hi-Temp	25	13.78	Ambient	1.13	-	Half Cut	No Cut
8	$Ti/KClO_4$	150	206.9	Ambient	1.08	0.625	Cut	Nominal Cut
9	$Ti/KClO_4$ (33/67)	150	103	Ambient	1.00	0.663	Cut	Deep Cut
10		125	103	Ambient	1.26	0.558	Cut	Deep Cut
11		100	103	Ambient	1.20	1.197	3 Strands Left	Scratch
12		112	103	Ambient	1.20	0.748	Cut	Nominal Cut
13		120	103	-54° C	0.97	0.749	Cut	Nominal Cut
14		120	103	-54° C	1.00	0.726	Cut	Nominal Cut
15		120	103	+95° C	1.02	0.756	Cut	Nominal Cut
16		120	103	+95° C	1.00	0.705	Cut	Nominal Cut
17	(33/67) $Ti/KClO_4$	120 No Shear Pin Used	103	Ambient	1.20	0.661	Cut	Nominal Cut

5. For a reduced shear pin diameter, the area ratio to obtain the desired 2224 N failure is the ratio of the desired force (2224 N) to the actual force required to shear the 1.575 mm diameter pin (2976 N) times the ratio of the calculated shear strength (459 MPa) of the 1.575 mm diameter pin to the shear strength (753) MPa) actually obtained. The area ratio is

$$\frac{2224 \text{ N}}{2976 \text{ N}} \times \frac{459 \text{ MPa}}{753 \text{ MPa}} = 0.456 \quad .$$

The cross section area of the 1.575 mm diameter pin is 1.948 mm^2. The required area for the pin to fail at 2224 N is:

$$\Delta = 0.456 \; (1.948 \text{ mm}^2) = 0.8883 \text{ mm}^2 \; ,$$

for which the required pin diameter is:

$$D = \frac{0.8883 \text{ mm}^2}{0.7854}^{1/2} = - 0.063 \text{ mm} \quad .$$

Because of a further reduction in the internal volume of the prototype cutter design, a standard wire diameter at 1.016 mm was selected for the shear pin.

V. Prototype Design Studies

Electrostatic Characterization of Header Subassembly

The reefing line cutter is required to withstand, without initiating, electrostatic discharge pulses typical of a charged human body condition. As an aid in achieving this capability, there is an external spark gap path of 0.2 mm to 0.3 mm from the bridgewire terminal tabs to the actuator housing.

Electrostatic Tests With a Capacitor Discharge Pulse -- Fifty actuator headers were subjected to capacitor discharge voltage pulses using a UN-326 Electrostatic Discharge Tester having a 600-pF capacitance and 500 ohms series resistance. Charge voltage on the capacitor was increased for each breakdown path. The magnitude of the breakdown voltage was observed by a memory oscilloscope. Headers were evaluated for a room temperature condition as well as for submersion in freon on the spark gap and charge cavity end. An aluminum slug was used to simulate the pyrotechnic charge for a number of these tests. Electrostatic standoff capability of the header is summarized in Table VI.

Electrostatic Tests With a Ramp Voltage Pulse -- Thirty headers were subjected to pulse testing from a ramp voltage generator that could provide a peak voltage within 4 ms. The data obtained from this series of tests is summarized in Table VII.

TABLE VI

Summary of Electrostatic Standoff Capability of the MC3133 Header Assembly

- **ESD Test Results - Voltage Discharge from a 600 pF Capacitor w/500 ohm Series Resistor**

Breakdown Voltage (KV)

		No Slug				With Slug (Al)			
Mode	Statistic	Pin to Pin	Pin 1 to Case	Pin 2 to Case	Shorted Pin to Case	Pin to Pin	Pin 1 to Case	Pin 2 to Case	Shorted Pin to Case
Dry in Air	$\bar{x}$	2.98	1.85	1.80	1.76	0.96	1.80	1.79	1.72
	σ	0.49	0.35	0.38	0.32	0.55	0.31	0.31	0.31
	Max	4.20	2.50	2.70	2.50	2.40	2.50	2.50	2.50
	Min	2.10	1.20	1.20	1.30	0.30	1.20	1.20	1.20
	n	50	50	50	50	50	50	50	50
Tab End in Freon	$\bar{x}$	12.15	8.41	8.54	8.37	1.13	8.70	8.74	8.47
	σ	1.72	1.47	1.43	1.44	0.41	1.25	1.25	1.20
	Max	14.50	12.50	12.00	12.00	1.90	12.00	10.50	10.70
	Min	7.00	5.80	5.50	5.50	0.30	5.40	5.40	5.40
	n	50	50	50	50	50	50	50	50
Freon in Charge Cavity	$\bar{x}$		2.78		1.80				
	σ		0.50		0.29				
	Max		3.70		2.20				
	Min		2.00		1.30				
	n		8		8				

NOTE: ESD tester was UN326.

TABLE VII

Ramp Voltage Breakdown Test Results

- **Ramp voltage peaks in 4.0ms**

Mode	Statistics	Pin to Pin	Shorted Pin to Case	Pin to Pin w/Slug
Dry in Air	$\bar{x}$	2.48	1.50	0.85
	σ	0.40	0.31	0.56
	Max	3.10	2.10	2.50
	Min	1.60	0.95	0.40
	n	30	30	30
Freon at Tab End	$\bar{x}$	-	-	1.11
	σ	-	-	0.65
	Max	<4	-	1.80
	Min	-	-	0.40
	n	30	-	30
Freon in Charge Cavity	$\bar{x}$		1.40	2.36
	σ		0.27	0.33
	Max		1.60	2.70
	Min		1.00	2.00
	n		30	30

Pyrotechnic Train

Selection of the materials used in the pyrotechnic train of the prototype actuator was based on achieving reasonably good electrostatic pulse standoff, a high no-fire capability as evidenced by a relatively high thermal ignition temperature and good sensitivity to the required 5.0 ampere, 7.5 ms firing pulse.

A pyrotechnic mixture of 33/67 titanium subhydride/potassium perchlorate ($TiH_{.65}/KClO_4$) was initially selected for both the ignition and output charge material. During the course of evaluating this material, ignition delays and large bridgewire delta resistance changes were observed. The problems encountered are the result of the thermal coefficient of expansion and electrical conductivity characteristics of $TiH_x/KClO_4$. Because of this, it was decided to use this material only as an output charge.

A 20/80 formulation of boron/calcium chromate ($B/CaCrO_4$) was selected for the ignition charge. This material has good ignition sensitivity, and its thermal coefficient of expansion closely matches alumina ceramic, which is the charge holder material in the actuator header.

It does, however, have a slower burning rate than $TiH_x/KClO_4$. A column height was therefore designed with sufficient length to achieve reliable ignition and minimum burning time.

Three different ignition charge increments were evaluated. The charge weights and expected column heights were:

Charge Weight (mg)	Expected Column Height (mm)
12	0.6
32	1.5
42	2.0

The expected delay for the 12-mg increment was 6 ms. Evaluation of three groups of actuator-cutters showed minimal variation in bridge resistance before and after powder consolidation and during thermal cycling from -62° C to 90° C. Ignition sensitivity to a 5-ampere firing pulse was good, ranging between 1.241 and 1.388 ms at a -62° C temperature environment. All units functioned and cut the nylon test cord completely. The $TiH_{.65}/KClO_4$ output charge weight for the three groups of actuators was varied in order to completely fill the charge cavity; the weights were 110, 84, and 75 mg. Using powder column heights and functional data, an analysis was made to determine the burn rates of the $B/CaCrO_4$ and the $TiH_{.65}/KClO_4$. The respective inverse burn rates are calculated to be 5.79 ms/mm and 0.38 ms/mm. Delay time versus column height for the $B/CaCrO_4$ is shown in Figure 8.

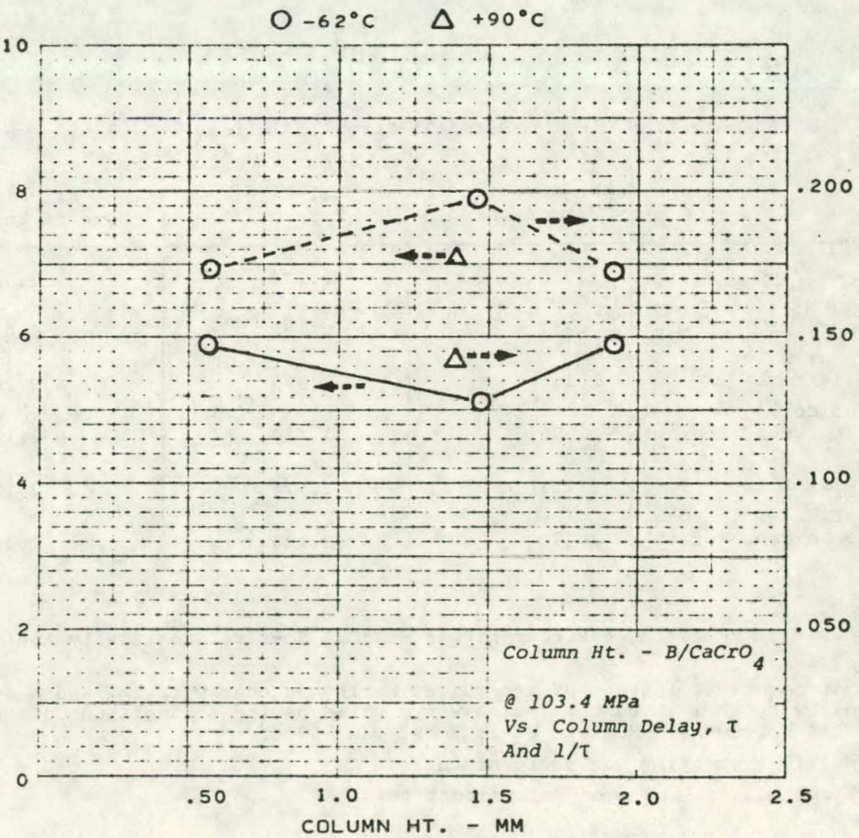


Figure 8. Delay Time vs Column Height

The above series of tests resulted in the selection of 12 mg of $B/CaCrO_4$ for the initiator charge and 84 mg of $TiH_{.65}/KClO_4$ for the output charge. Further verification of performance was then obtained for a temperature environment of 90° C.

Firing Sensitivity -- The actuator for the reefing line cutter must reliably initiate, given a 5-Adc, 7.5-ms pulse. The sensitivity of the actuator design to several input no-fire, all-fire stimuli was determined by the Langlie one-shot method of sensitivity testing. The attributes data were analyzed by the ASCENT program.

The no-fire current level was determined for a sample of 60 actuators that were at 74° C and were subjected to a set of current levels; if the actuator did not initiate within 5 minutes, the test was considered a success. The all-fire current level was determined for a sample of 35 actuators that were at -54° C and were subjected to a set of current levels; if the actuator did not initiate within 7.5 ms, the test was considered a failure. An additional all-fire sensitivity test was performed for a sample of 34 actuators to determine the effect of one 0.5-Adc, 600-ms pulse followed by ten 24-Vdc, 1.0-μs ($\cong$0.5 MJ each) no-fire pulse.

The results obtained from the various no-fire, all-fire sensitivity tests show that the MC3133 reefing line cutter meets design intent. The data are summarized in Table VIII.

TABLE VIII

Summary of MC3133 No-Fire/All-Fire Sensitivity(1)

	No-Fire Current (A)(3)	All-Fire Current (A)	All-Fire After No-Fire Environment (A)(2)
Estimated Mean Current	1.958	2.379	2.509
Estimated Standard Deviation of Current	0.257	0.128	0.071
Estimated Level at Which 0.1 Percent Will Fire	1.165	1.983	2.289
Lower 97.5% Confidence Limits on 0.1 Percent Point	1.000(4)	1.618	2.147
Estimated Level at Which 99.9 Percent Will Fire	2.751	2.776	2.728
Upper 97.5% Confidence Limits on 99.9 Percent Point	3.170	3.120	2.867

NOTES:

(1) All-fire sensitivity testing environment was -54°C. No-fire sensitivity environment was +74°C.

(2) No-fire environment was a train of ten pulses having an energy of .5mJ and a duration of 1µs. Following this, a current pulse was applied having an amplitude of 0.50 ampere with a duration of 600ms. No-fire environment was -54°C.

(3) No-fire sensitivity testing was performed at +74°C.

(4) Lower 80.0% confidence limits on 0.1 percent point.

Ignition or Bridgewire Burnout Time as a Function of Firing Current -- During the course of the development program, a number of tests were performed to define bridgewire burnout time on ignition time and cutter performance versus firing currents of 3.5, 5, 10, and 15 amperes. Data from these tests are plotted in Figures 9, 10, and 11.

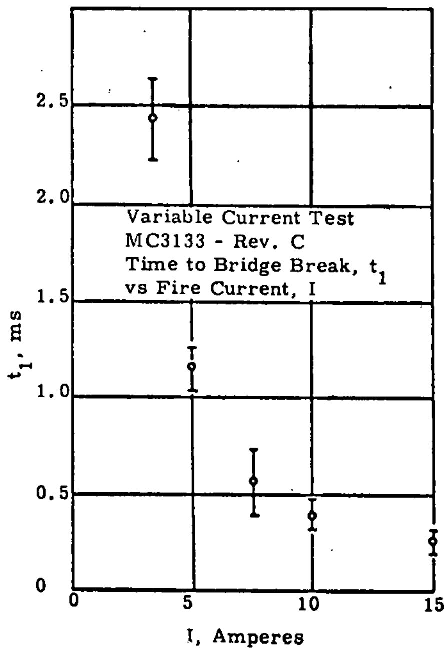


Figure 9. Firing Current versus Bridgewire Break on Ignition Time.

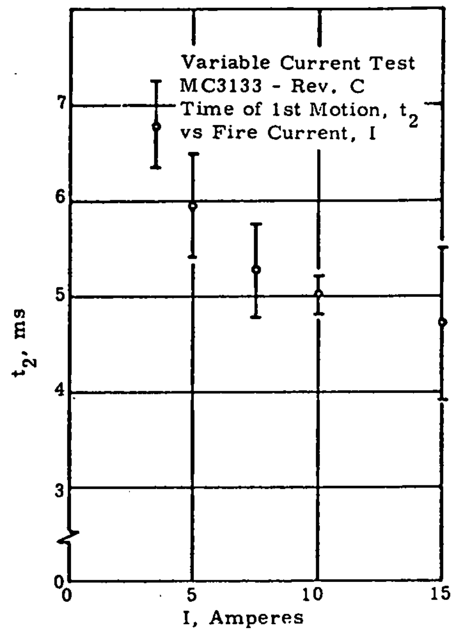


Figure 10. Firing Current versus Time to First Motion of the Cutter Blade

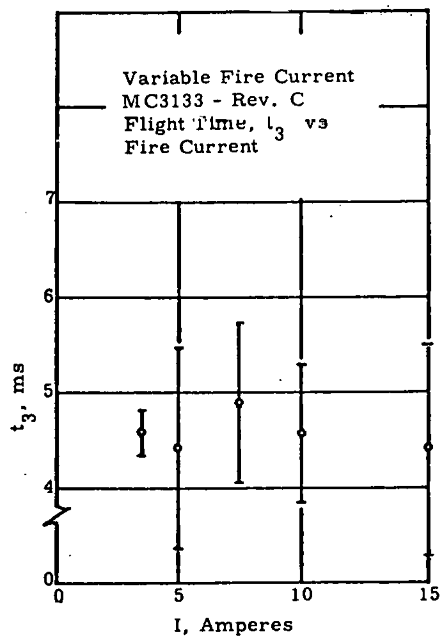


Figure 11. Firing Current versus Flight Time of the Cutter Blade

VI. Design Verification

Electrostatic Discharge (ESD) Pulse Susceptibility Tests

Electrostatic discharge (ESD) pulse susceptibility tests were conducted on ten MC3133 reefing line cutters. The test pulse was from a 600-pF capacitor charged to 20 kV and then discharged through a 500-ohm resistor in series with the bridgewire circuit. The discharge pulse was applied three times. Prior to the first pulse, and after the third pulse, an electrothermal response (ETR) measurement was made of the bridgewire-pyrotechnic interface. The data from this series of tests are presented in Table IX. The ETR test is discussed in more detail in the next section of this report.

TABLE IX

Summary of Effects of Electrostatic Discharge (ESD) Pulse Testing in the MC3133 versus Normal Response of the Bridgewire-Pyrotechnic Interface

• Before ESD

Statistic	Initial Bridge Resistance (Ω)	Initial Theta (θ), °C	Initial Gamma (γ), μW/°C
$\bar{x}$	1.009	88.8	5809
σ	0.045	16.9	1223
Upper Value	1.113	118.8	7619
Lower Value	0.949	67.9	4201
n	10	10	10

• After ESD

Statistic	Initial Bridge Resistance (Ω)	Initial Theta (θ), °C	Initial Gamma (γ), μW/°C
$\bar{x}$	0.989	103.9	4824
σ	0.022	17.4	980
Upper Limit	1.026	127.8	6825
Lower Limit	0.955	73.9	3736
n	10	10	10

NOTE:
ESD tester was UN326. Standard pulse as defined in SS302365 (discharge from a 600 pF capacitance circuit charged to 20KV through a 500 ohm series resistance).

Following the above testing, the group of MC3133s were then evaluated for functional performance. Data are presented in Table X which compare functional performance to that of a control group which had not been subjected to ESD or ETR testing.

TABLE X

Summary of Electrostatic Discharge (ESD) Pulse Testing on MC3133 Functional Performance

Statistic	Time of Bridgewire Break, t_1 (ms)		Time of First Motion, t_2 (ms)		Flight Time of Cutter Blade, t_3 (ms)	
	ESD Test	Control	ESD Sample	Control	ESD Sample	Control
$\bar{x}$	1.334	1.221	5.841	6.279	0.537	0.554
σ	0.082	0.088	0.359	0.364	0.048	0.027
Max	1.452	1.360	6.288	6.898	0.573	0.610
Min	1.220	1.117	4.962	5.843	0.417	0.529
n	10	10	10	10	10	10

NOTES:

Test temperature 23°C.

Tester was UN326. Standard ESD test pulse per SS302365 (600 pF capacitor charged to 20KV and with 500 ohm series resistance).

A statistical F and T test indicates that the difference between the two groups for the mean values of t_1 and t_2 is quite significant for the 95% confidence level.

Electrothermal Response Testing

The electrothermal response test (ETR) is a nondestructive method of characterizing the bridgewire/pyrotechnic interface of an electropyrotechnic device. It produces an analog of resistance change in response to a square wave electrical signal. In the ETR test, as performed by Sandia, five values are determined from a single pulse: R_o, θ, γ, C_p, and τ, where:

R_o = initial bridgewire resistance (Ω)

θ = temperature rise (°C)

$\gamma = \alpha I^2 R_o^2/\Delta R$ = thermal conductivity of material surrounding the bridgewire (μW/°C)

- α = coefficient of thermal resistivity
- I = pulse current
- ΔR = change in resistance resulting from the increase in temperature

$C_p = I^2 R_o^2/m$ = heat capacity of material surrounding bridgewire (μJ/°C)

- m = initial pulse slope (mΩ/ms)

$\tau = \frac{C_p}{\gamma}$ time constant (ms) .

In order to characterize the bridgewire-pyrotechnic interface of the actuator, a group of six reefing line cutters were assembled and subjected to ETR tests. Following this, they were then fired along with another group of six cutters which had not been subjected to ERT testing to determine the effects on functional parameters. The ETR data are summarized in Table XI. The values of theta and gamma obtained were in the expected ranges.

TABLE XI

Summary of Electrothermal Response Testing for the MC3133 Reefing Line Cutter

S/N	Resistance R_o (ohms)	Theta (θ, °C)	Gamma (γ, µW/°C)	C_p (µJ/°C)	Tau (ms)
420	1.009	93.3	5308	30.52	5.75
421	1.043	69.0	7424	35.29	4.75
422	1.050	76.0	6780	34.17	5.04
423	1.028	108.3	4657	28.84	6.19
424	1.007	80.3	6158	30.25	4.91
425	1.007	81.1	6099	31.93	5.23
Mean	1.024	84.7	6071	31.83	5.31
Std Dev	0.019	14.1	992	2.47	0.55

Notes:
1) Units were pulsed with 700 Ma
2) Alpha taken at 130 µohm/ohm/°C
3) Gamma calculated at 75 ms

Bridgewire resistance (BWR) measurements were made for all 12 cutters. Following ETR testing, BWR measurements were again performed. No significant change in BWR was observed.

The cutters were test fired at room temperature to compare functional performance in order to determine if ETR testing had any effect on the bridgewire-pyrotechnic interface which affected bridgewire burnout or ignition time (t_1) as well as start of motion (t_2) and flight time (t_3) of the cutter blade. The data are summarized in Table XII.

TABLE XII

Summary of MC3133 Performance With and Without an Electrothermal Response (ETR) Nondestructive Test Environment

- With ETR Pulse - 700 mA, 80 ms pulse

Statistic	Theta (θ), °C	Gamma (γ), µW/°C	Bridgewire Burnout Time, t_1 (ms)	First Motion of Cutter Time, t_2 (ms)	Flight Time of Blade, t_3 (ms)
$\bar{x}$	84.7	6071	1.226	6.118	0.405
σ	14.1	992	0.049	0.184	0.032
Upper Value	108.3	7424	1.273	6.401	0.433
Lower Value	69.0	4657	1.150	5.951	0.357
n	6	6	6	6	6

- Without ETR Pulse

Statistic	Theta (θ), °C	Gamma (γ), µW/°C	Bridgewire Burnout Time, t_1 (ms)	First Motion of Cutter Time, t_2 (ms)	Flight Time of Blade, t_3 (ms)
$\bar{x}$	-	-	1.151	5.960	0.442
σ	-	-	0.039	0.180	0.035
Upper Value	-	-	1.203	6.129	0.509
Lower Value	-	-	1.108	5.624	0.406
n	-	-	6	6	6

NOTE:
A statistical F and T test indicates the difference between the two groups for the mean values of t_1 and t_3 is significant for the 95% confidence level.

The values of t_1, t_2 and t_3 were subjected to a statistical F & T test. The significant differences obtained in these analyses were differences in t_1 and t_2. The variation, or longer time from current application to bridgewire burnout, is attributed to the current pulse of the ETR test. The change in t_3 values is probably normal considering the small test sample size.

Environmental Test Series

A series of MC3133 reefing line cutter tests were made before and after various environments as part of the design verification of the cutter. The results obtained from these tests shown that the specified environments had no adverse effect on MC3133 performance. A statistical summary of the design verification testing after exposure to various environments is provided in Table XIII.

TABLE XIII

Summary of MC3133 Design Verification Testing After Sequential Environmental Exposure

Statistic	Bridge Burnout Time, t_1 (ms)			First Motion of Cutter Blade, t_2 (ms)			Flight Time of Cutter Blade, t_3 (ms)		
	-55°C	23°C	90°C	-55°C	23°C	90°C	-55°C	23°C	90°C
$\bar{x}$	1.213	1.151	1.144	6.779	5.960	6.027	0.443	0.442	0.405
σ	0.064	0.039	0.053	0.414	0.180	0.215	0.045	0.035	0.036
Lower Value	1.274	1.203	1.214	7.866	6.129	6.287	0.552	0.509	0.469
Upper Value	1.126	1.108	1.079	6.446	5.624	5.584	0.386	0.406	0.353
n	10	6	10	10	6	10	10	6	10

NOTES:

Sample tested at 23°C was a control group and was not exposed to sequential environments.

Sequential environments were: thermal shock, -55°C to 90°C; mechanical shock, 9806 m/s^2, 1.5 to 2.0ms duration; sine vibration, 98/ms^2, 26 to 2000 Hz; acceleration 1960 m/s^2, 2 minutes each axis.

Kevlar reefing line cord having 60KN tensile strength was used.

Hard faced connector was used for these tests.

These units had cutter blades per Issue C of 308160.

Modified Cutter Blade Evaluation

During the latter part of the development program, several cutter blades fractured during a test series. Two failure modes occurred. Either the entire forward section of the blade tip broke off or the blade fractured in a longitudinal direction which allowed venting of the internal gas pressure. An analysis of the design was made which resulted in several design changes to the blade. The internal cavity depth and the radius at the bottom of the cavity was changed, along with a slight increase in blade length and a revision in the heat treat condition from a Rockwell hardness of C59-62 to C52-56.

To evaluate the modified blade design, four cutters were fabricated with an increased pyrotechnic charge load of 120-125 mg, which represents an approximate overtest of 40 percent. Two cutters were then test fired at a temperature environment of -62° C and two at 90° C. The tests resulted in complete cutting of the kevlar cord. The blades were inspected and found to be in excellent condition.

Following the above overtests, five additional cutters containing the standard 84 mg pyrotechnic charge load were fired at each temperature environment of 23° C, -62° C and 90° C. These cutters performed within the expected limits of function. The data are summarized in Table XIV.

TABLE XIV

Summary of MC3133s Having a Modified Blade Design and Test Fired at Three Temperature Levels

Statistic	Test Temperature 23° C $\bar{x}$	23° C σ	-62° C $\bar{x}$	-62° C σ	90° C $\bar{x}$	90° C σ
t_1, ms (bridgewire) burnout	1.185	0.046	1.208	0.022	1.135	0.089
t_2, ms (first motion of blade)	6.090	0.093	6.322	0.145	5.556	0.251
t_3, ms (flight time of blade)	0.476	0.057	0.521	0.029	0.548	0.077

A comparison of cutter performance for both blade designs is shown in Table XV.

TABLE XV

Comparison of Cutter Performance for Both Blade Designs

Rev. C - Blade Mass 18.70 gm (1)

Statistic	Time of Bridgewire Break, t_1 (ms) -55°C	23°C	90°C	Time of First Motion of Blade, t_2 (ms) -55°C	23°C	90°C	Flight Time of Blade, t_3 (ms) -55°C	23°C	90°C
$\bar{x}$	1.213	1.151	1.144	6.779	5.960	6.027	0.443	0.442	0.405
s	0.064	0.039	0.033	0.414	0.180	0.215	0.045	0.035	0.036
Max	1.274	1.203	1.214	7.866	6.129	6.287	0.552	0.509	0.469
Min	1.126	1.108	1.079	6.446	5.624	5.584	0.386	0.406	0.353
n	10	6	10	10	6	10	10	6	10

Rev. D - Blade Mass 20.15 gm (2)

Statistic	Time of Bridgewire Break, t_1 (ms) -55°C	23°C	90°C	Time of First Motion of Blade, t_2 (ms) -55°C	23°C	90°C	Flight Time of Blade, t_3 (ms) -55°C	23°C	90°C
$\bar{x}$	1.208	1.185	1.135	6.322	6.090	5.556	0.521	0.476	0.548
s	0.022	0.046	0.089	0.145	0.093	0.251	0.029	0.057	0.077
Max	1.230	1.228	1.231	6.530	6.180	5.848	0.562	0.534	0.636
Min	1.179	1.142	1.052	6.200	5.974	5.242	0.489	0.400	0.427
n	5	5	5	5	5	5	5	5	5

Identity of Test Groups:

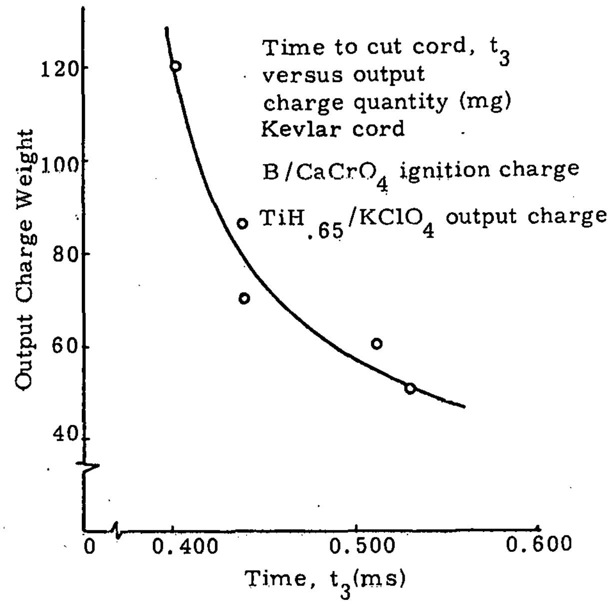
(1) Design verification test unit series.

(2) Revision D blade tests of 05-7999.

Pyrotechnic Charge Weight Marginality Tests

To demonstrate the adequacy of the cutter to sever Kevlar cord and to further characterize performance, a series of tests was conducted for cutters having various pyrotechnic charge weights. The tests results obtained show that the MC3133 will perform its functional requirements with a pyrotechnic charge weight as low as 50 mg. The data are plotted in Figure 12.

Figure 12. Flight Time of Blade verses Output Charge Weight of $TiH_{.65}/KClO_4$



Design Improvements for Severing Kevlar Cord

During the development program, the majority of the Kevlar reefing line test cords were coated with a 15-percent solution of polyvinyl butyrate and/or beeswax. Stiffening the cord in the area to be severed provides a more uniform cut. However, during high temperature (90° C) testing, it was observed that several of the Kevlar strands were not being cleanly cut and were being trapped between the top portion of the knife edge of the cutter blade and the housing. To prevent or minimize this condition the beeswax was replaced with a Sergene coating. This material, which is available from General Plastics Corporation, is a formulated solution of nylon resin, water, and alcohol. It is designed to minimize fabric fraying after a cutting operation. Also, two teflon inserts having a semicircular configuration were incorporated to position the Kevlar cord, which is considerably thinner than the nylon cord, to the horizontal centerline of the blade.

Twenty test firings were then performed, as follows:

Group	Sample Size	Cord Type	Test Temperature (° C)
1	10	Kevlar/Sergene	+90
2	5	Kevlar/Sergene	-62
3	5	Kevlar/Sergene	+90

The significant parameters for the three groups of data are summarized in Table XVI.

TABLE XVI

Evaluation Results of MC3133s Having Teflon Inserts and Severing Sergene Coated Kevlar

Group	1		2		3	
Cord Description	Kevlar/Sergene		Kevlar/Sergene		Kevlar	
Test Temp., °C	+90		-62		+90	
Statistic	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
t_1, ms *(bridge break)*	1.121	0.060	1.210	0.044	1.066	0.035
t_2, ms *(first motion)*	5.535	0.243	6.088	0.141	5.386	0.142
t_3, ms *(flight time)*	0.542	0.062	0.618	0.033	0.590	0.055
Dent Depth, mm	1.710	0.194	1.166	0.186	1.290	0.269

VII. Safe Handling Tests

As with any pyrotechnic or explosive device, the MC3133 Reefing Line Cutter should be handled with care and using a safe operating procedure. The reefing line cutter assembly does not include the mating cable/connector CF2339 or CF2371.

As a safety feature, the cutter assembly is provided with an aluminum cap which shorts the actuator bridgewire terminals to the cutter housing. This cap also prevents the actuator from being projected as a missile in a backward direction from the cutter blade if an inadvertent firing should occur; the probability of such a firing occurring is remote.

To emphasize the importance of the shorting cap, as well as the observance of a safe handling procedure, a test firing was performed using an MC3133 Reefing Line Cutter without shorting cap. This duplicates an assembly condition in which the cap is removed prior to the installation of the cable/connector and an inadvertent firing occurs. Movement of the actuator was recorded by a high speed camera. The results of this test are shown in Figure 13, which is a plot of velocity versus time as the actuator is propelled backward out of the cutter blade. The test also is demonstrated that the cord can be severed even though the actuator is not restrained.

An additional test firing with camera coverage was performed to observe movement of the blade as it severed a Kevlar cord. Blade velocity versus time is shown in Figure 14.

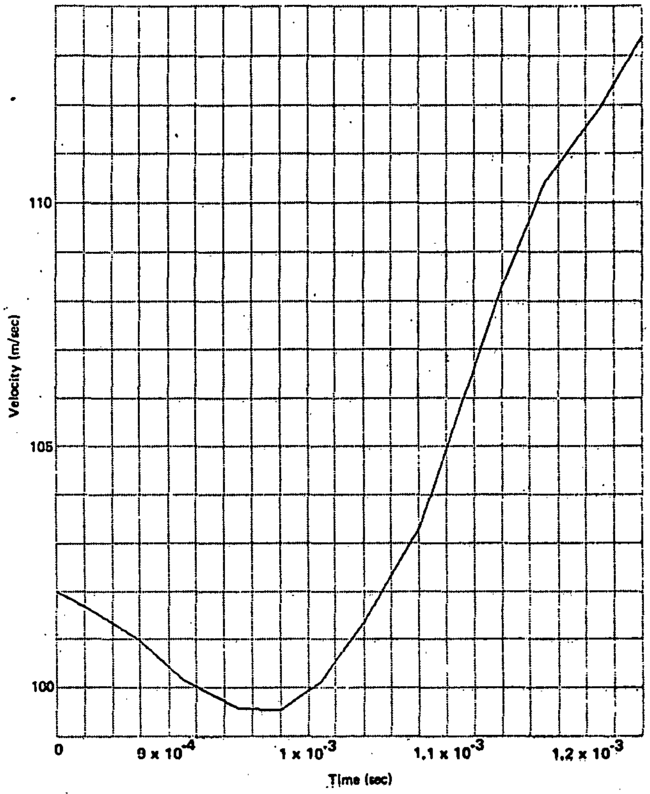


Figure 13. Velocity of Actuator When Not Restrained by a Safety Cap or Connector/Cable - Inadvertent Firing Condition

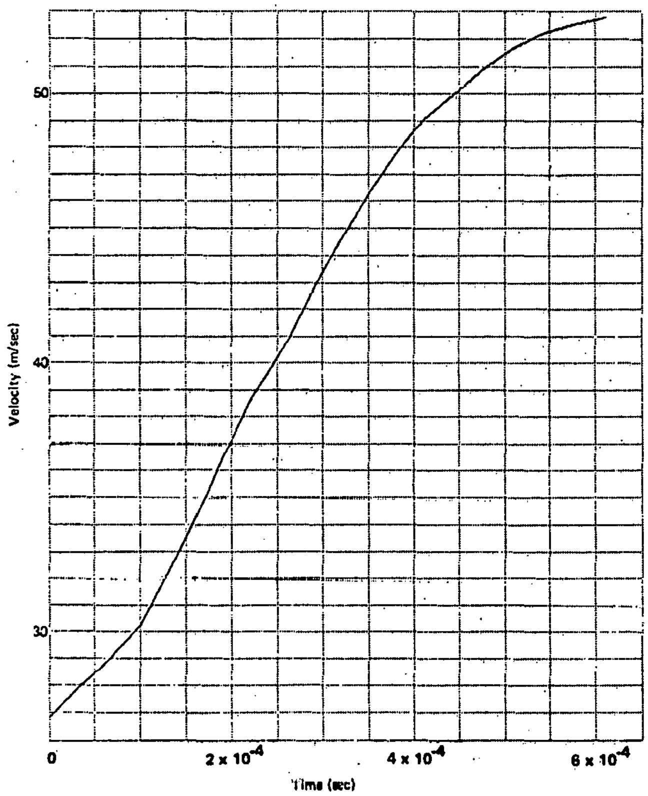


Figure 14. Velocity of Blade versus Time for Severing Kevlar

VIII. Conclusions

A pyrotechnic actuated reefing line cutter was developed for use in applications where a programmable time delayed firing signal to a reefing line cutter is provided by means of an interconnecting cable that is attached to one of the shroud lines of a parachute.

Development test data show that the MC3133 Reefing Line Cutter is more than adequately designed to reliably perform its function of severing either a nylon or Kevlar reefing line cord over a temperature range of -62° C to 90° C.

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