HDL-TM-75-5

Inertial Impact Switches for Artillery Fuzes
Part III: Rocket Application

TM-75-5—Inertial Impact Switches for Artillery Fuzes Part III: Rocket Application—by G. Lucey, Jr., S. Clark, Jr., T. Zimmerman, M. Ressler

April 1975

U.S. Army Materiel Command
HARRY DIAMOND LABORATORIES
Adelphi, Maryland 20783

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-TM-75-5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Inertial Impact Switches for Artillery Fuzes, Part III, Rocket Application		5. TYPE OF REPORT & PERIOD COVERED Technical Memo[redacted]
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) G. Lucey, Jr., T. Zimmerman S. Clark, Jr., M. Ressler		8. CONTRACT OR GRANT NUMBER(s) Customer Order No. R11X375201 F1F0
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, Md 20783		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Project Manager, 2.75 in. Rockets		12. REPORT DATE Apr[redacted]75
		13. NUMBER OF PAGES 24p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

HDL [redacted] 732291

AMCMS Code: 4810163?320

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Inertial	Early
Impact	Premature
Switch PD	
Point Detonating	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An early function of the FMU-98 fuze mounted on the 2.75-in. rocket occurred approximately 0.1 sec after mechanical arming. Circumstantial evidence is documented that indicates the 600-G, Skinny inertial switch to be the cause. The theory is that the switch had a deformed gap and was excited into closure by rattling of the rocket fins and sputtering of the rocket motor. Although the evidence is not conclusive on the cause of the early function,

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(continued)

a precautionary change to the less resonant, 600-G, low cost switch is recommended.

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1. INTRODUCTION

The FMU-98 fuze experienced an early function on 28 Sept 1973. The fuze was mounted on a low-spin (30 rps), 2.75-in. rocket with a Mk 40 motor and an M151 warhead. Motion pictures showed the rocket was nearly 1.3 sec into flight before the explosion. The early function occurred after mechanical arming (~1.2 sec), and definitely before burnout of the motor (1.5 sec), because the exhaust plume could be seen exiting the fireball. This timing diverts attention from the fuze electronics to mechanical components, such as the inertial impact switch shown in figure 1.

In-flight vibration data obtained on a test rocket showed that significant vibration occurred near the early function time (fig. 2). The hypothesis is that one or more fins of the rocket were rattling due to sputtering of the rocket exhaust. The rattle was presumably the result of a very loose mounting of the fins on the motor casing. Since rattle and sputtering induce flexural, torsional, and axial vibrations in the rocket, the concern is that the resultant acceleration vector was capable of exciting the inertial impact switch into closure. An investigation of this hypothesis is presented in this report.

The comments here are directed at the performance of inertial impact switches* employed on the low-spin, 2.75-in. rocket only, and no extrapolation should be made to spinning-type artillery rounds. High spin tends to render a switch quite insensitive to vibrations in flight; this topic has been treated experimentally.[1]

2. ROCKET VIBRATION

A triaxial accelerometer described in table I was mounted on a test rocket and used to collect three channels of the in-flight data pictured in figure 2. Figures 3 through 6 show portions of data from an axial and a radial accelerometer near the time of motor burnout. The telemetered data from the second radial accelerometer are not available—the telemetered frequencies were 52.5, 93, and 165 kHz, and the tunable discriminator used to dub the data onto magnetic type required for digitizing analog data was limited to 125 kHz. Consequently, only two channels of data are available, and a precise acceleration analysis cannot be performed.

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[1] *"Inertial Impact Switches For Artillery Fuzes, Part I: Development," R. Thiebeau and G. Lucey, Jr., HDL-TM-72-18, Harry Diamond Laboratories Washington, D, C, 20438.*

**The switches discussed in the text are nicknamed Skinny, Fat, and Low Cost, according to their shape or method of manufacture. The operating principles of the three switches are identical, and G ratings are used to denote sensitivities to closure. (Note: The symbol "G" in this report represents the word, "GEES," and has no numerical value or units.)*

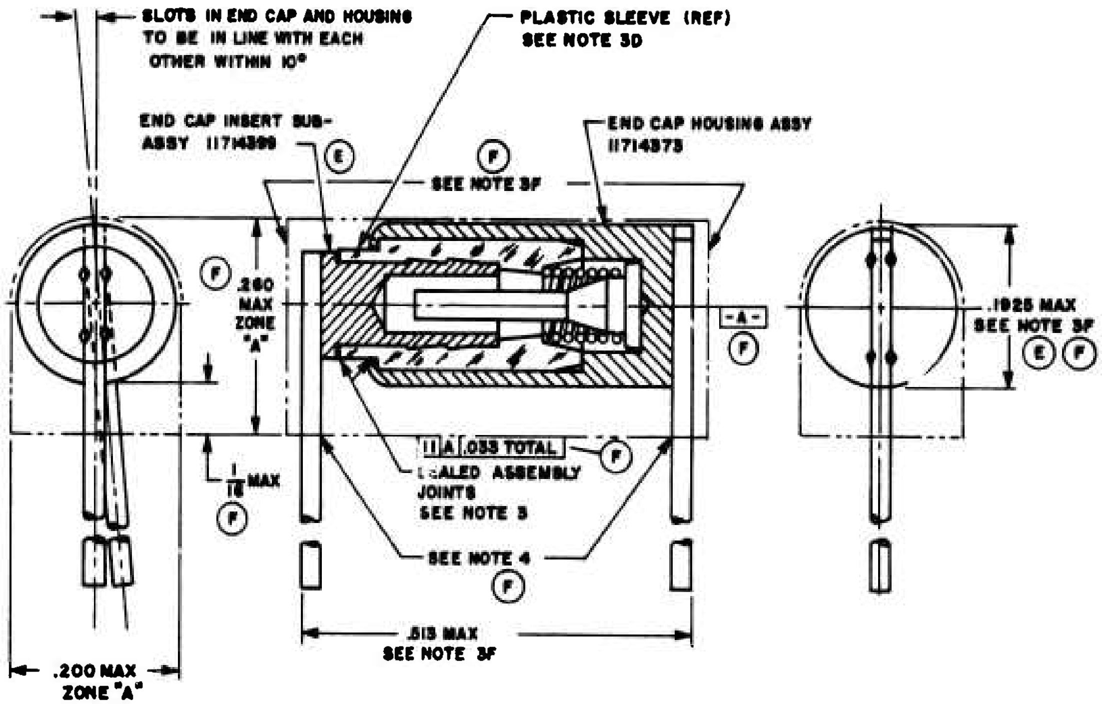


Figure 1. Skinny switch used in the FMU-98 rocket fuze (600 G), the M429E1 rocket fuze, and the M514A1E1 artillery fuze (300 G). (Spec control drwg #11714370)

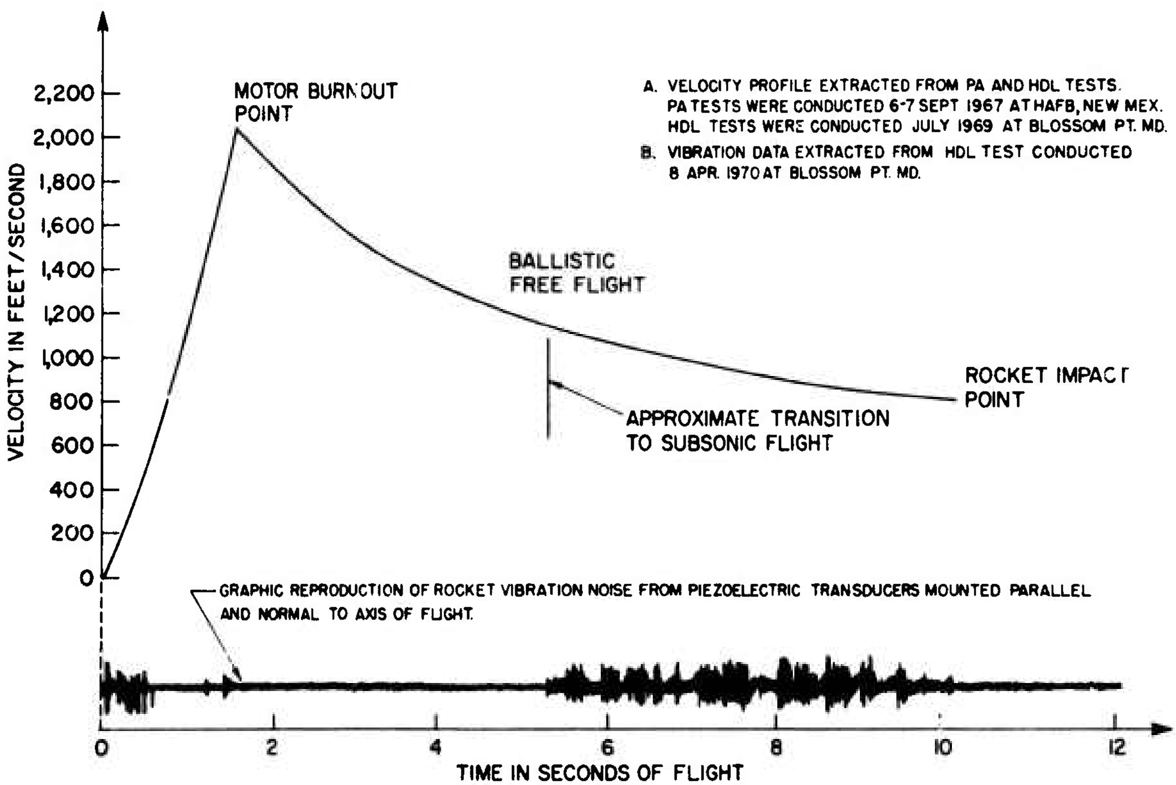


Figure 2. Velocity profile and vibration data for M429 fuze ground launched via 2.75-in. rocket/Mk40 motor.

TABLE I. TRIAXIAL ACCELEROMETER DATA

Manufacturer: Wilcoxon Research
Model: 129

NOTE: Voltage sensitivity and capacitance refer to conditions at the end of the cable, including a 100-pF external capacitance.

	Axis		
Property	X	Y	Z
Charge sensitivity pC/G	8	8.6	7.9
Voltage sensitivity mV/G	13.5	13.5	13.5
Capacitance (pF)	590	630	590
Transverse sensitivity % Z	3.5	2	1.5
Frequencies (kHz) for the following increases in voltage sensitivity			
0%	0.1	0.1	0.1
6%	2.3	2.7	2.7
12%	3.4	4.0	4.0
41%	5.5	6.7	6.7

Even if all channels of data were available, a precise analysis would be difficult because the vector summation of the accelerometer data does not describe the resultant acceleration of the rocket. The reason is that the tangential accelerations associated with the torsional vibrations were not measured, and must be deduced from the data. The approach involves trial and error calculations, and is quite complex and imprecise.

A circumstantial inquiry is possible, however. For example, figure 7 shows that the G levels in figures 3 through 6 are indeed small—that is, roughly 0.5 G. (Note that the thrust of the rocket is roughly 30 G, but this is not shown in the telemetered data because the bandpass lower limit of the accelerometer electronics is $\approx$ 20 Hz and the rocket pulse is lower than this value.) As a result, there is a tendency to conclude that a 600-G Skinny switch is quite safe

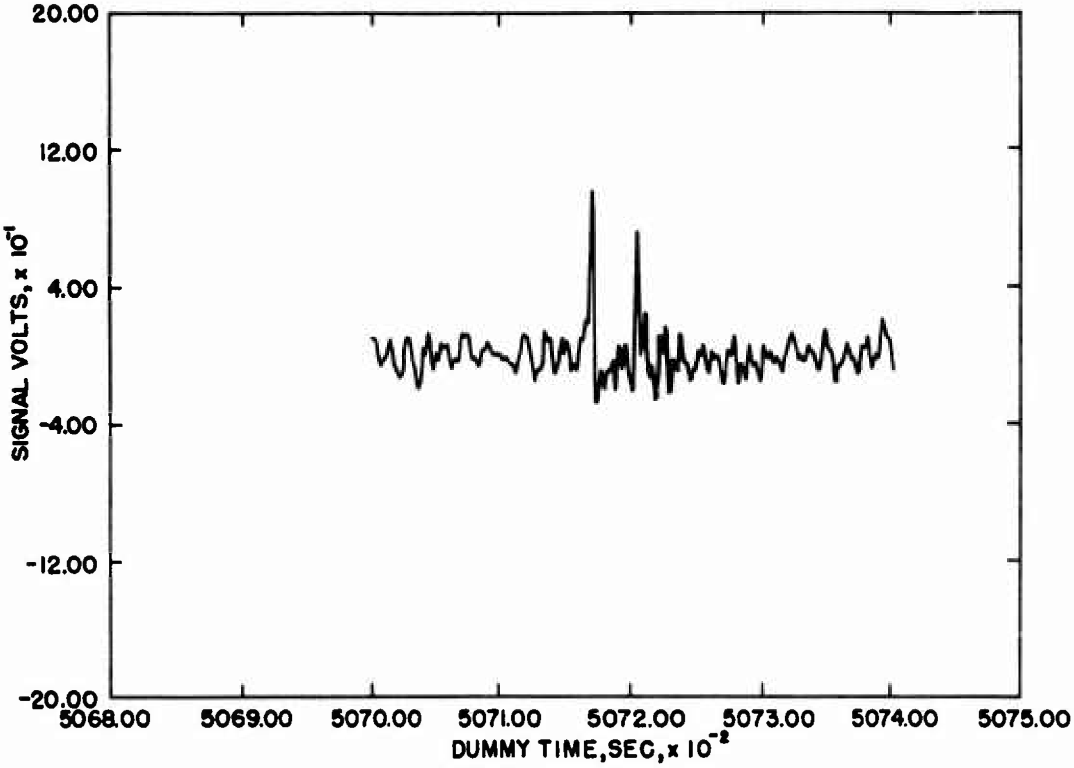


Figure 3. Radial accelerometer data at 1.2 sec, 0.04-sec duration.

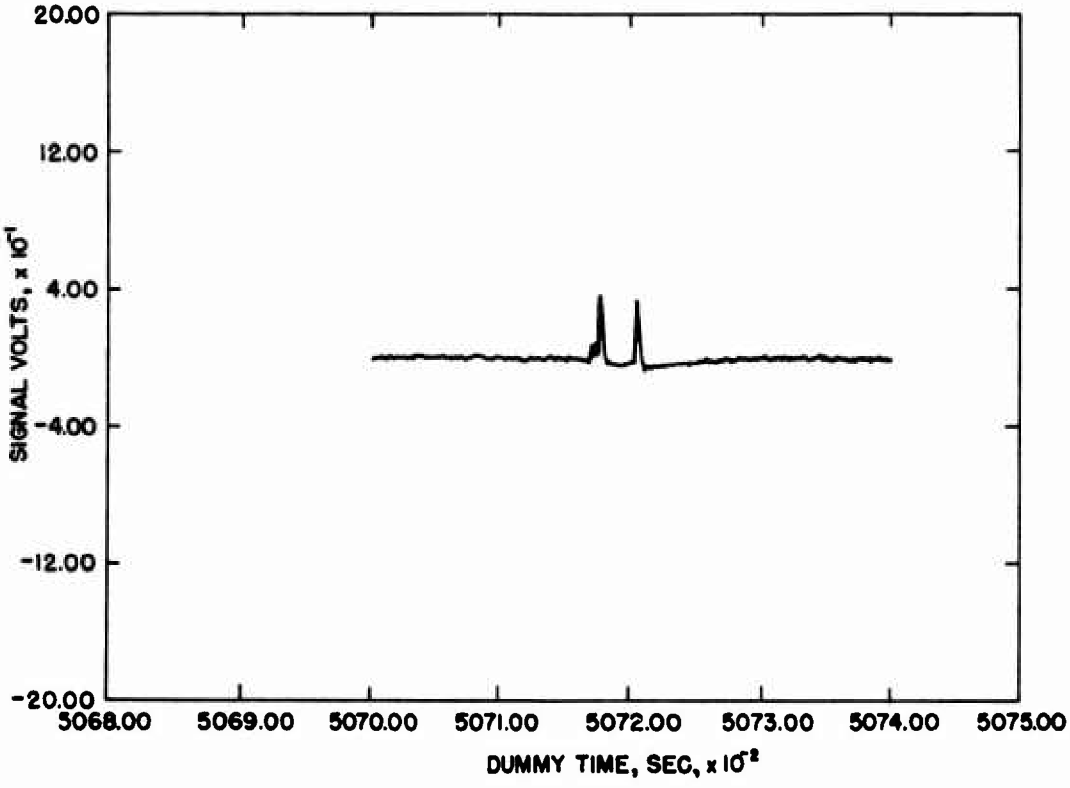


Figure 4. Axial accelerometer data at 1.2 sec, 0.04-sec duration.

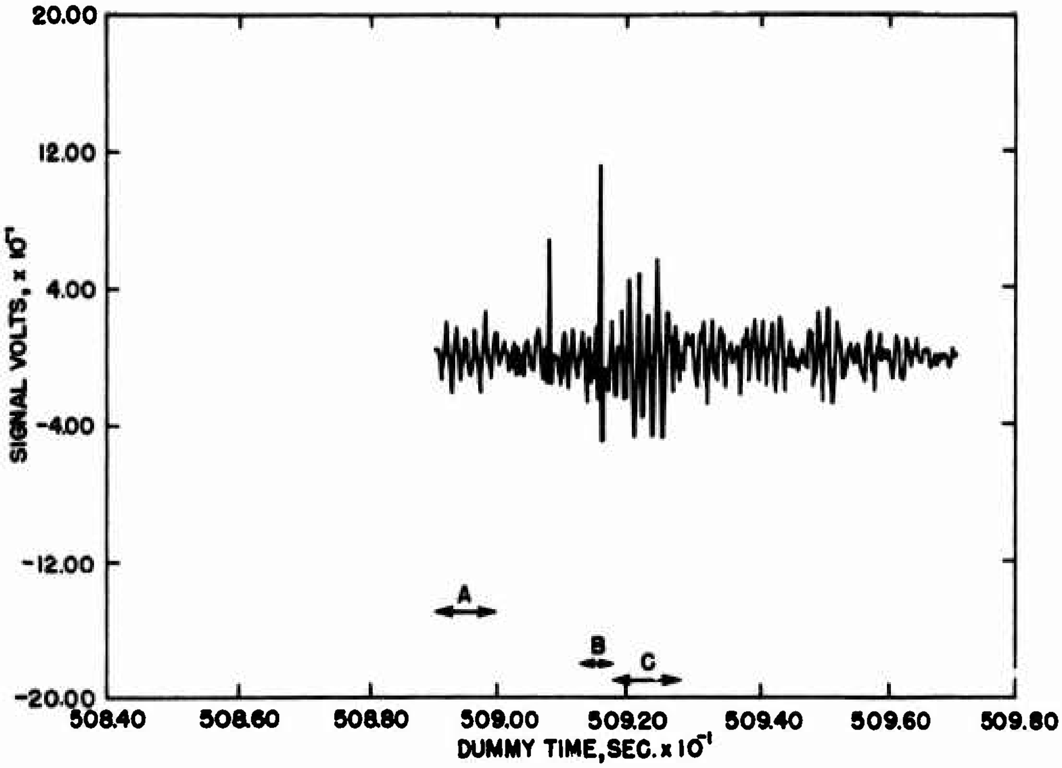


Figure 5. Radial accelerometer data at 1.5 sec, 0.08-sec duration.

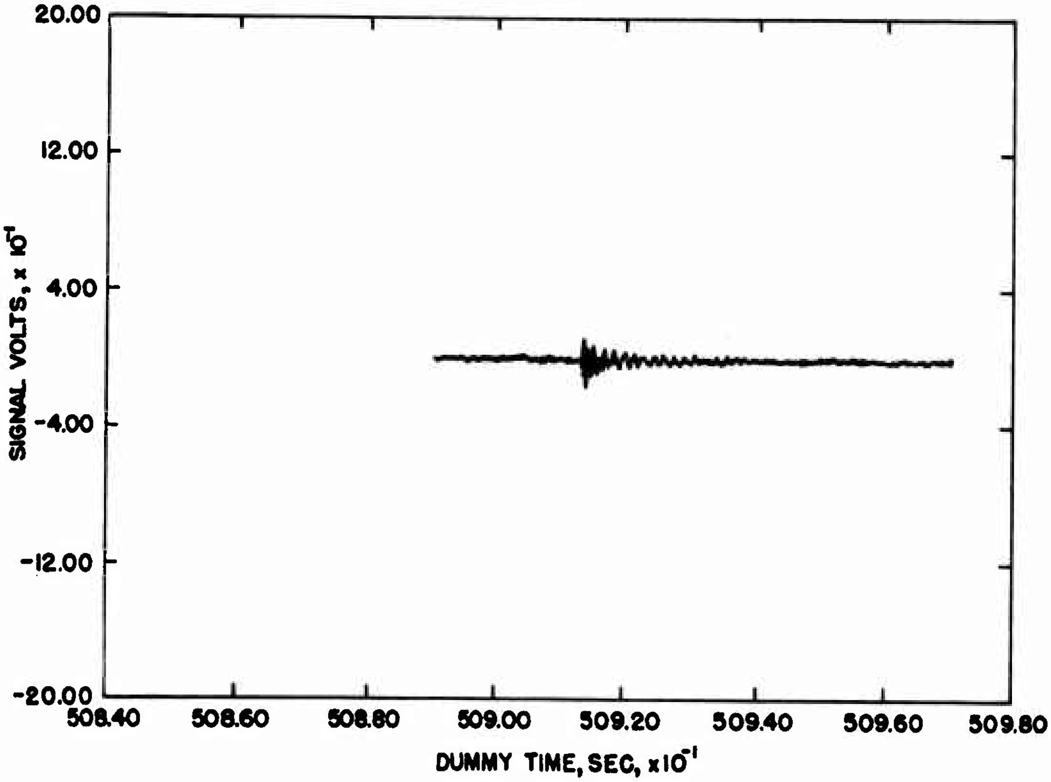


Figure 6. Axial accelerometer data at 1.5 sec, 0.08-sec duration.

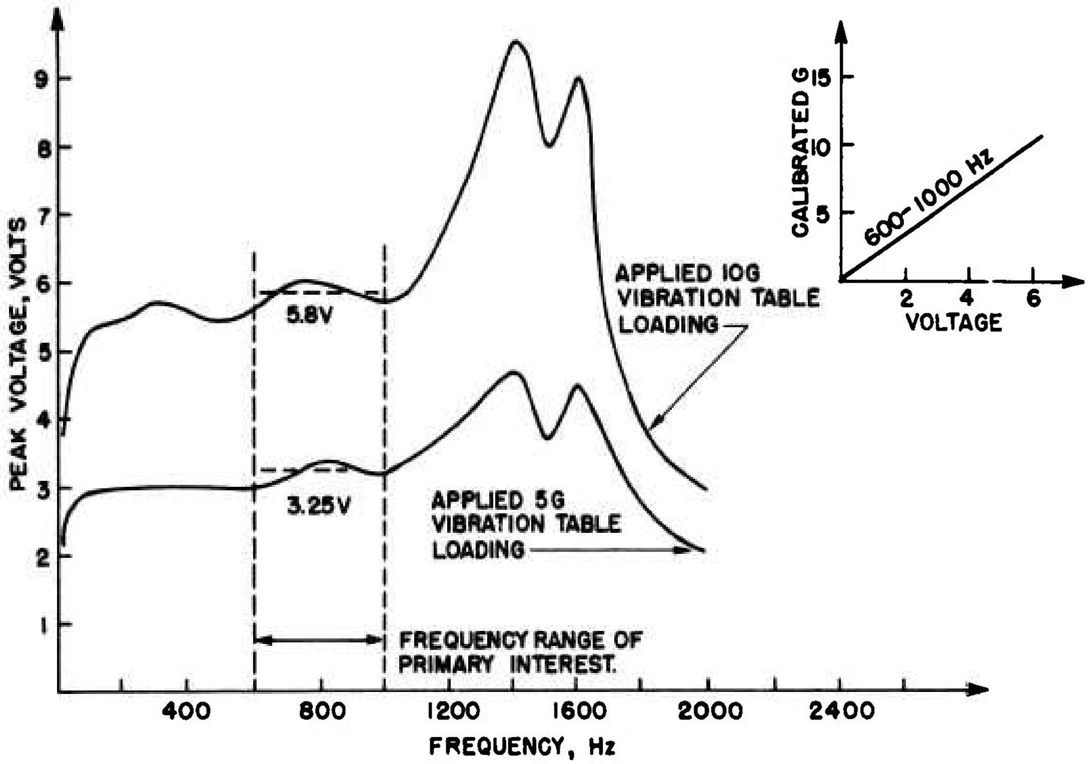


Figure 7. Telemetry calibration of the radial (x-axis) accelerometer.

from closure in flight. The tendency is reduced, however, by performing a worst-case analysis. Disregard flexure and assume all data from the radial accelerometer are due to torsional oscillation of the rocket in figure 8. The frequencies at which a point B oscillates between the extreme angle ϕ is Ω.

The radial position of B is R. The angular position of B at any time t is

$$\theta = \phi \sin \omega t \text{ where } \omega = 2\Pi\Omega . \qquad (1)$$

The radial G loading is the ratio of the radial acceleration and the acceleration of gravity, g.

$$G_r = \frac{R\dot{\theta}^2}{g} = \frac{R\phi^2\omega^2}{g} \cos^2\omega t . \qquad (2)$$

Similarly, tangential G loading is

$$G_t = \frac{R\ddot{\theta}}{g} = -\frac{R\phi\omega^2}{g} \sin \omega t . \qquad (3)$$

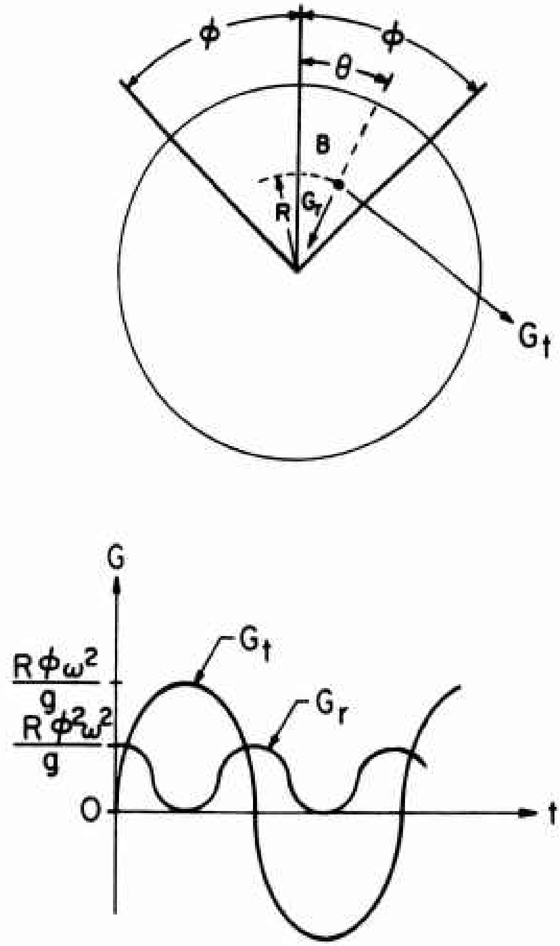


Figure 8. Torsional oscillation. Note that G_r is a peak-to-peak value, and that G_r has twice the number of peaks as G_t.

Eliminating ϕ,t shows

$$(G_t)_{max} = \omega\sqrt{\frac{R}{g}\,(G_r)_{max}} \quad . \qquad (4)$$

A count of the peaks in figure 7 shows the signal to be roughly 660 Hz and 0.5-G peak. Note that this measurement is made on a radial accelerometer. Equation (2) shows the radial accelerations due to torsion are all positive due to the cosine squared term; therefore, the peaks counted occur at twice the frequency of torsional oscillation and $(G_r)_{max}$ is a peak-to-peak measurement. Thus, $\omega = 2\Pi(330)$rad/sec and $(G_r)_{max} \approx 2(0.5\ G)$ in equation (4). The radial accelerometer is off center by the amount R = 0.41 in.; thus,

$$(G_t)_{max} \leq 2\pi\ (330)\sqrt{\frac{(0.41)\,(1.0)}{386}} \ , \qquad (5)$$

$$(G_t)_{max} \le 68 . \qquad (6)$$

This is not necessarily the correct value of $(G_t)_{max}$. The point to the calculation is that 0.5 G triaxial accelerometer readings do not imply low torsional tangential accelerations. Due to the radial direction of mounting the switch in the FMU-98 fuze, the tangential accelerations act upon the most sensitive plane of the switch; thus, there is concern about closure.

3. INERTIAL SWITCH SENSITIVITY

To assist in determining the marginality of the switch design, T. Zimmerman (HDL staff member) calculated the dynamic response characteristics based upon equations derived for the M728 Skinny switch. A report describing the derivation of the equations is in the final stages of preparation, and will be issued as part II of this study. Figure 9 shows the equations and calculated conditions for closure. Figure 10 shows the constants used in the calculations. Note that the switch specifications demand that the switch remain open under a G_c centrifuge loading of 300 G and closed under 1000 G. These are the two limits shown in figure 9. Due to the difficulties involved in analyzing the nonlinear vibrations of the switch, the calculations are valid only for steady forcing functions. Figure 11 shows that the equations used to describe the dynamic response are quite accurate.

4. SWITCH-ROCKET COMPATIBILITY

The range in dynamic sensitivities shown in figure 9 must be compared with the in-flight loadings estimated for the rocket. Figure 5 portrays the most severe of the two rocket shudders. Section A (fig. 5) shows the most commonly occurring sustained vibration, section B shows the most severe transient, and section C shows the most severe sustained vibration. A spectral analysis of these sections was performed by S. Clark, Jr. (HDL staff member) and the data and results are shown in figures 12 through 17.

For the sake of a worst-case analysis, assume the various spectra represent radial loadings associated with torsional vibrations of the rocket. A conversion to tangential loadings is necessary for comparison to the switch sensitivities. Note, however, that this comparison can be used only as an indicator of potential problems, nothing more. The reasons are twofold: (1) the $(G_t)_{max}$ calculations are admittedly high; and (2) the switch sensitivities in figure 9 are accurate only for steady, single-frequency loadings, which is not the case for the rocket vibrations shown in figures 13, 15, and 17. Unlike the situation with linear systems—whereby the motions of each component

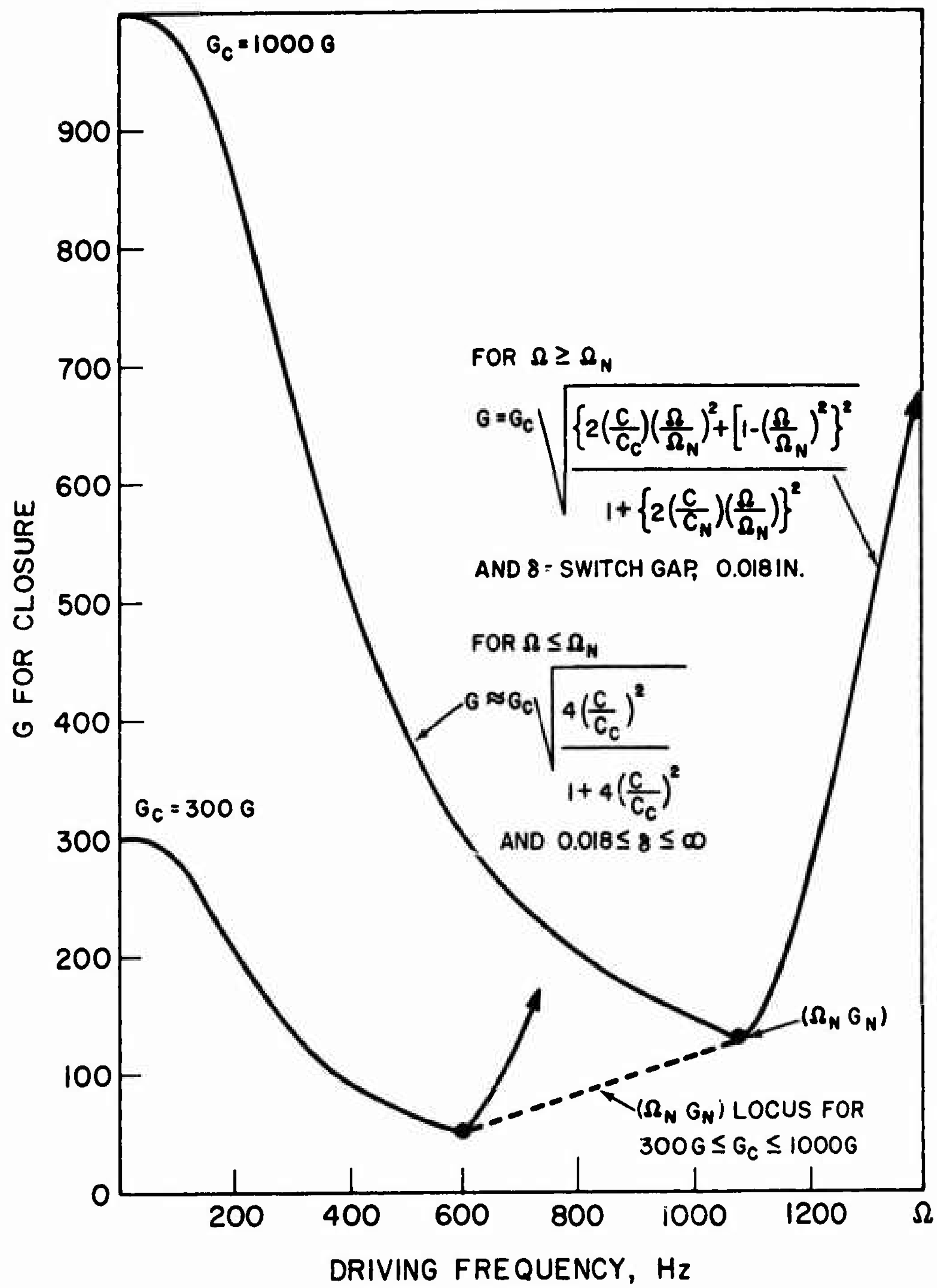
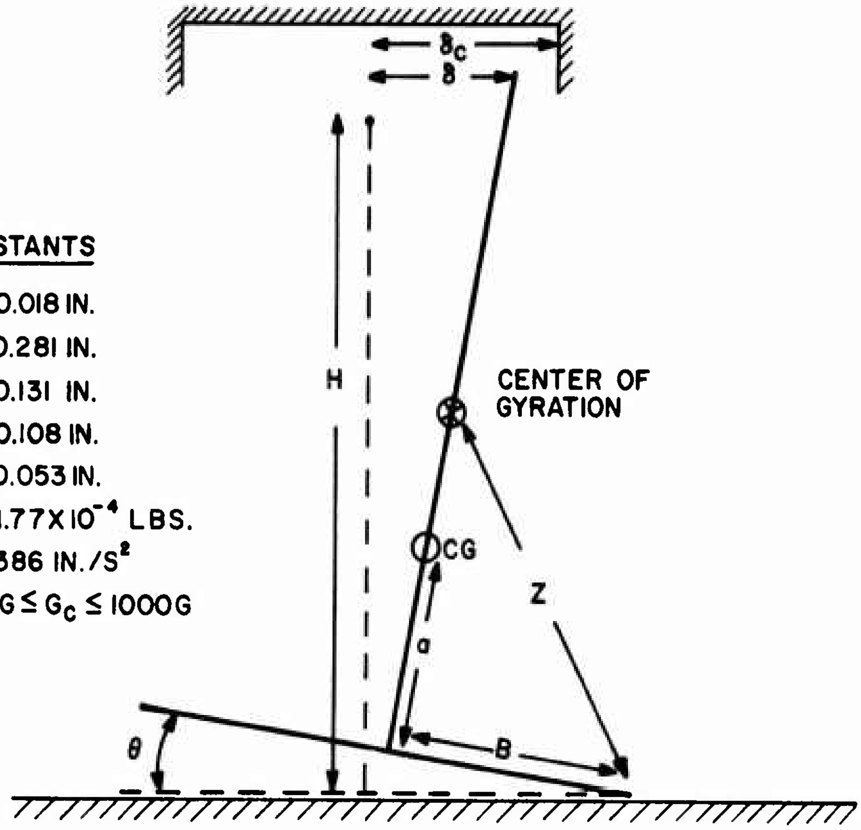


Figure 9. Closure conditions for steady-state vibrations of Skinny switches with various G_C ratings and a gap c^f 0.018 in.

loading are added to determine the overall motion—the principle of superposition does not hold with the nonlinear switch. It is quite possible that if one of the component rocket loadings could close the switch, the effect of the other components could be an interference with closure.



CONSTANTS

$\delta_C = 0.018$ IN.
$H = 0.281$ IN.
$Z = 0.131$ IN.
$a = 0.108$ IN.
$B = 0.053$ IN.
$W = 1.77 \times 10^{-4}$ LBS.
$g = 386$ IN./S^2
$300G \leq G_C \leq 1000G$

$$\Omega_N = \frac{1}{2\pi}(ke/Me)^{1/2}$$

$$C_C = 2(ke\ Me)^{1/2}$$

$$C_e = 0.093(\delta_C\ \Omega)^{1/2}$$

$$k_e = \frac{WHaG_C}{\delta Z^2}$$

$$Me = 0.81W/g$$

Figure 10. Properties of the FMU-98 Skinny switch.

To calculate the tangential loading, the procedure is to start with any signal frequency, f, and to note the decibel value. From the definition of decibel and the knowledge that 1.4-V peak is the reference, the peak-to-peak output voltage of the accelerometer at the given f is

$$V_f = 2(1.4)\log^{-1}(dB/20)\ . \qquad (7)$$

This voltage may be converted to G by means of the calibration curve in figure 7. Using the signal frequency, f, read the value of the calibrated accelerometer voltage, V_c, associated with a 5-G loading. Then, by proportionality,

$$(G_r)_{max} = \frac{5V_f}{V_c} \ . \qquad (8)$$

This value, along with equation (4) and the realization that for the tangential mode $\Omega = f/2$, permits calculation of the tangential rocket loadings shown in figure 18.

Figure 18 shows that the estimated rocket loadings are considerably higher than the range of dynamic sensitivities of production switches with the standard 0.018-in. gap, but below the sensitivities of switches modified to a 0.04-in. gap. There are two advantages to a wider gap. First, the frequency range to which switches are sensitive is moved away from the range at which the rocket experiences the strongest vibration. Second, the switch is less susceptible to assuming abnormal sensitivities below the 300-G minimum G_c rating as a result of deformations to the gap size during production, handling, and assembly into a fuze. Deformed switches have been observed in practice.

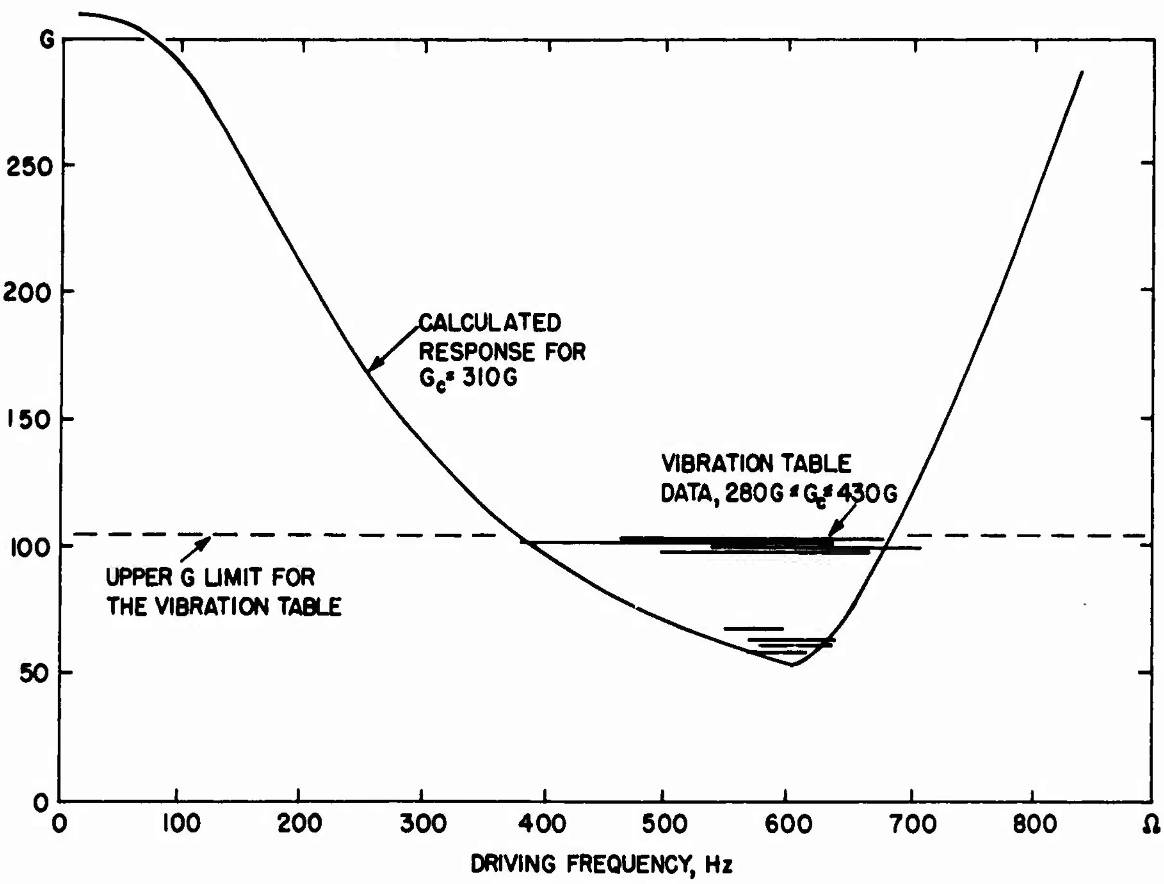


Figure 11. Comparison of the experimental and theoretical sensitivities of the M728 switch. The gap size was ~0.018 in. (Note: The horizontal lines indicate frequency ranges for switch closures measured at the G levels indicated.)

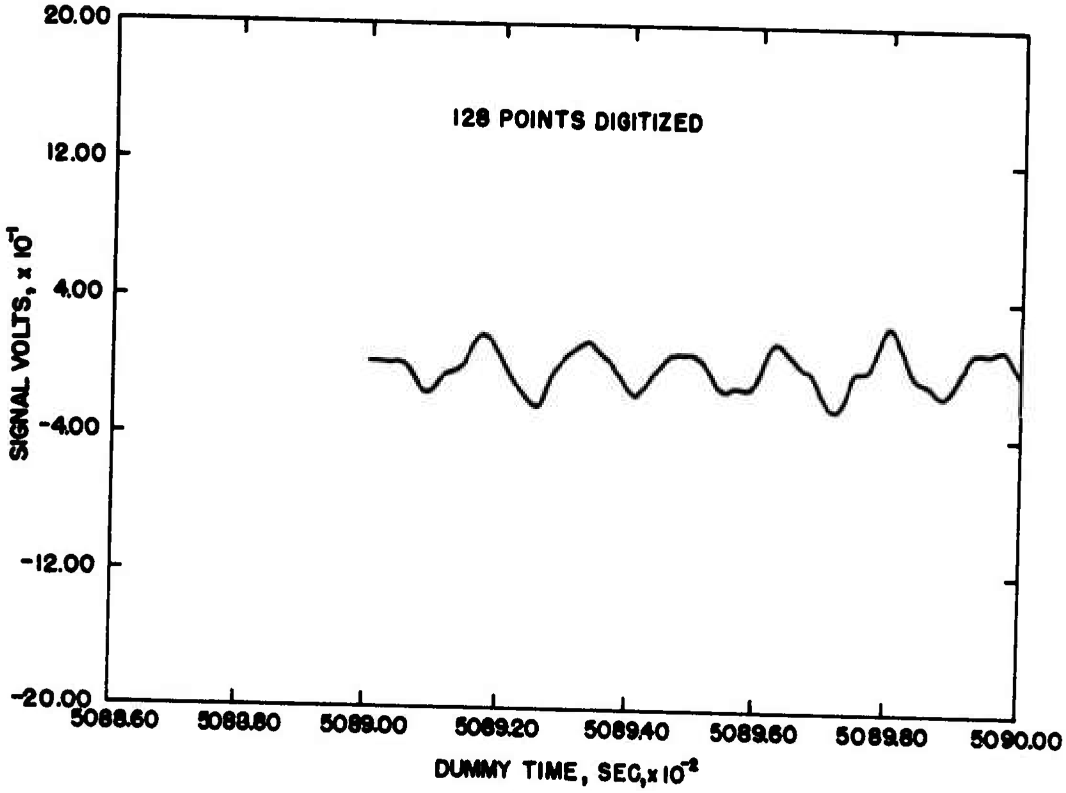


Figure 12. Time span "A" in figure 5.

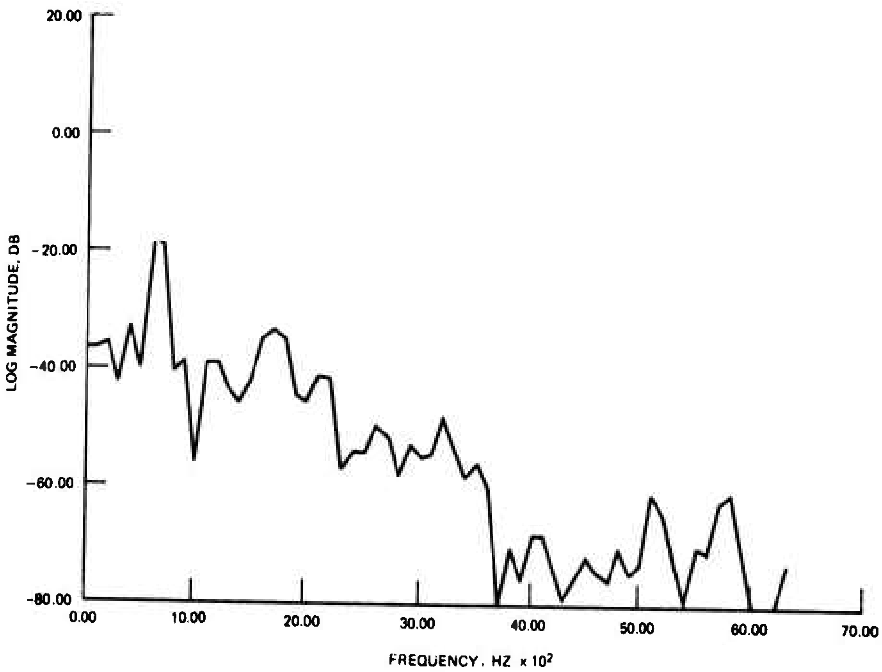


Figure 13. Frequency spectrum of figure 12.

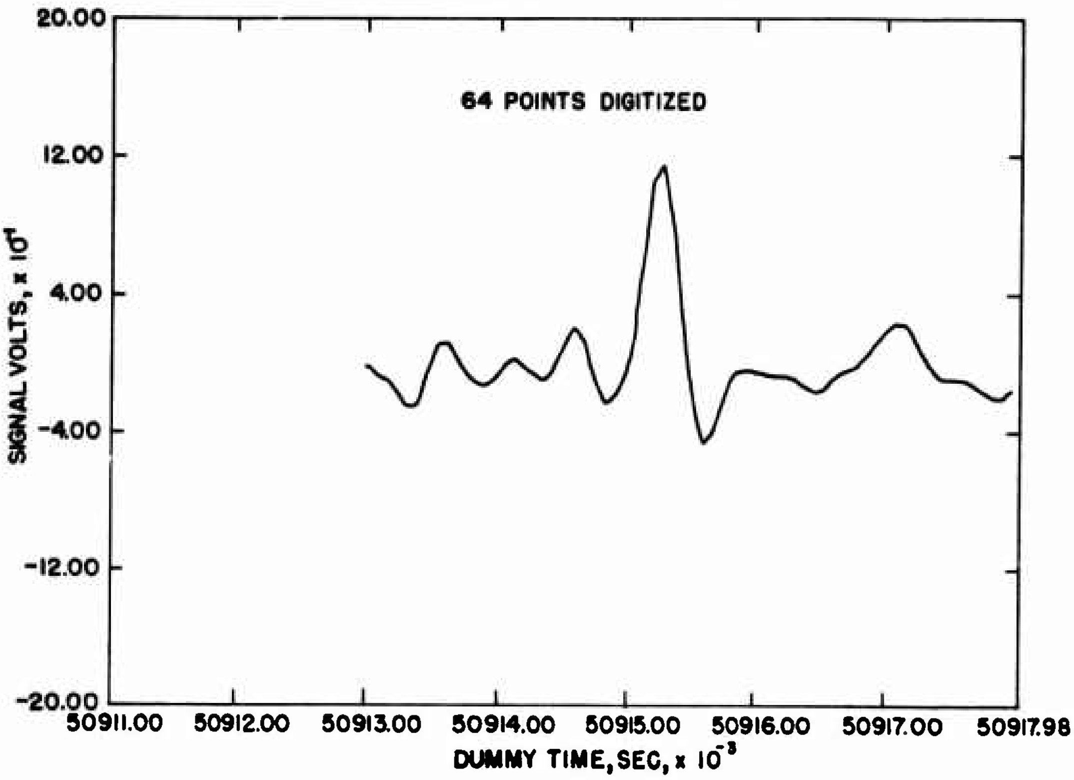


Figure 14. Time span "B" in figure 5.

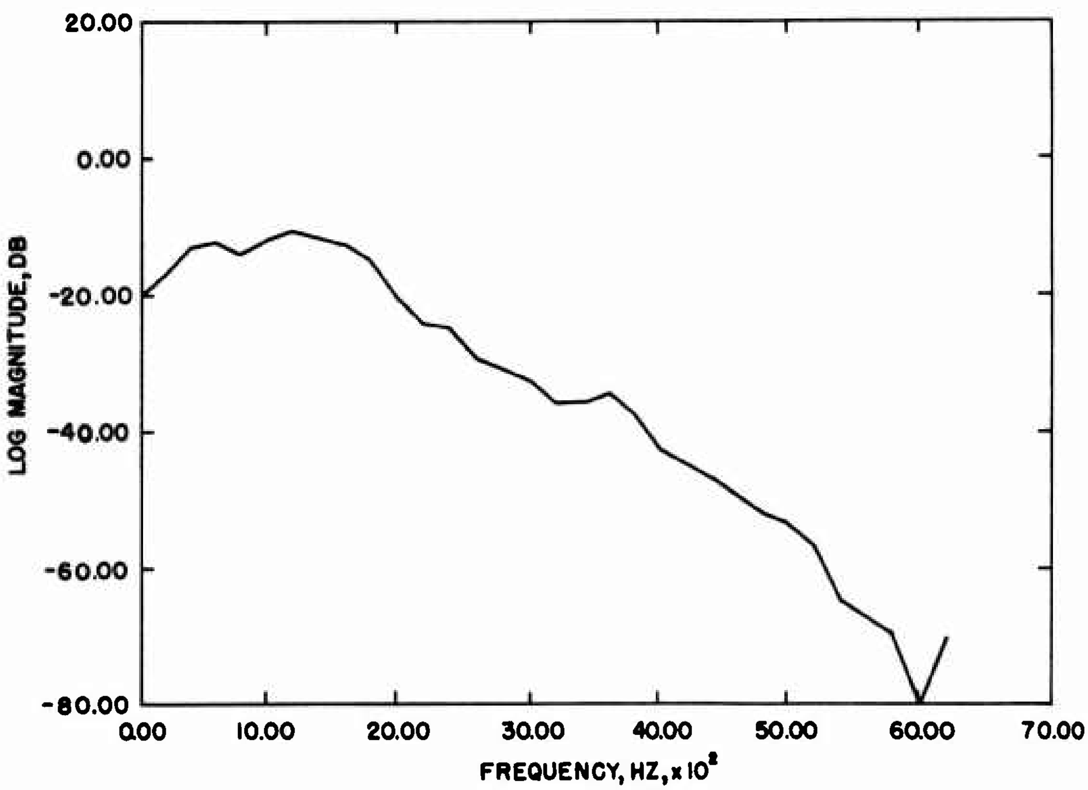


Figure 15. Frequency spectrum of figure 14.

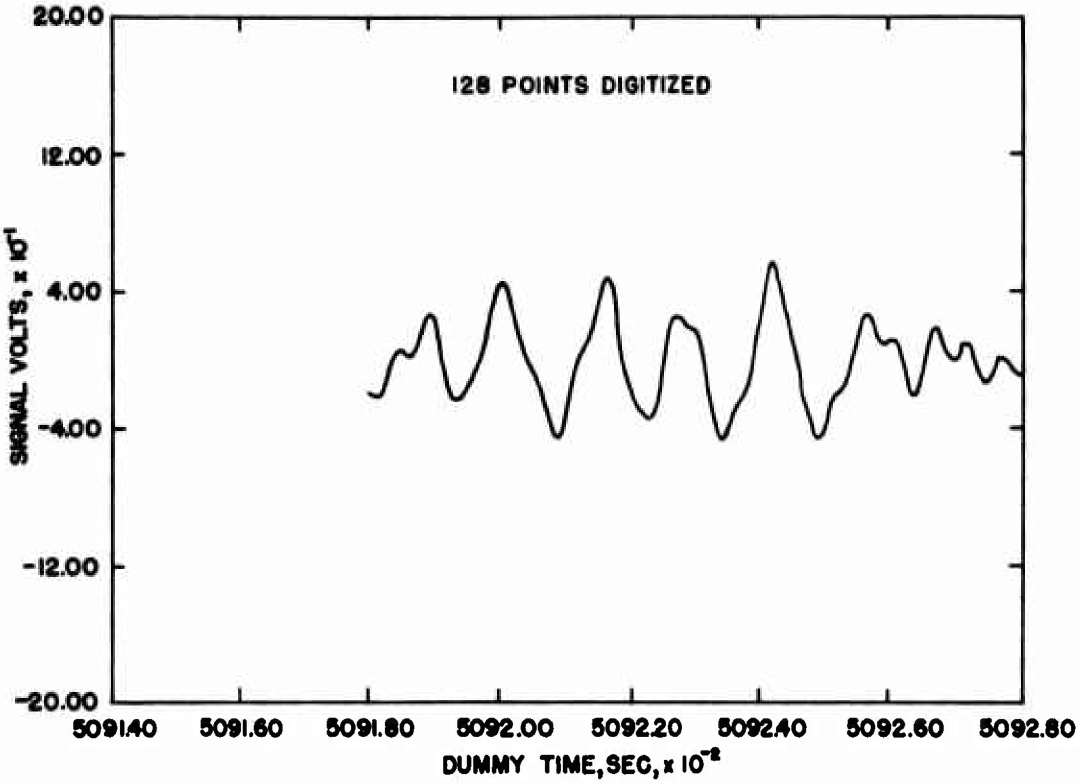


Figure 16. Time span "C" in figure 5.

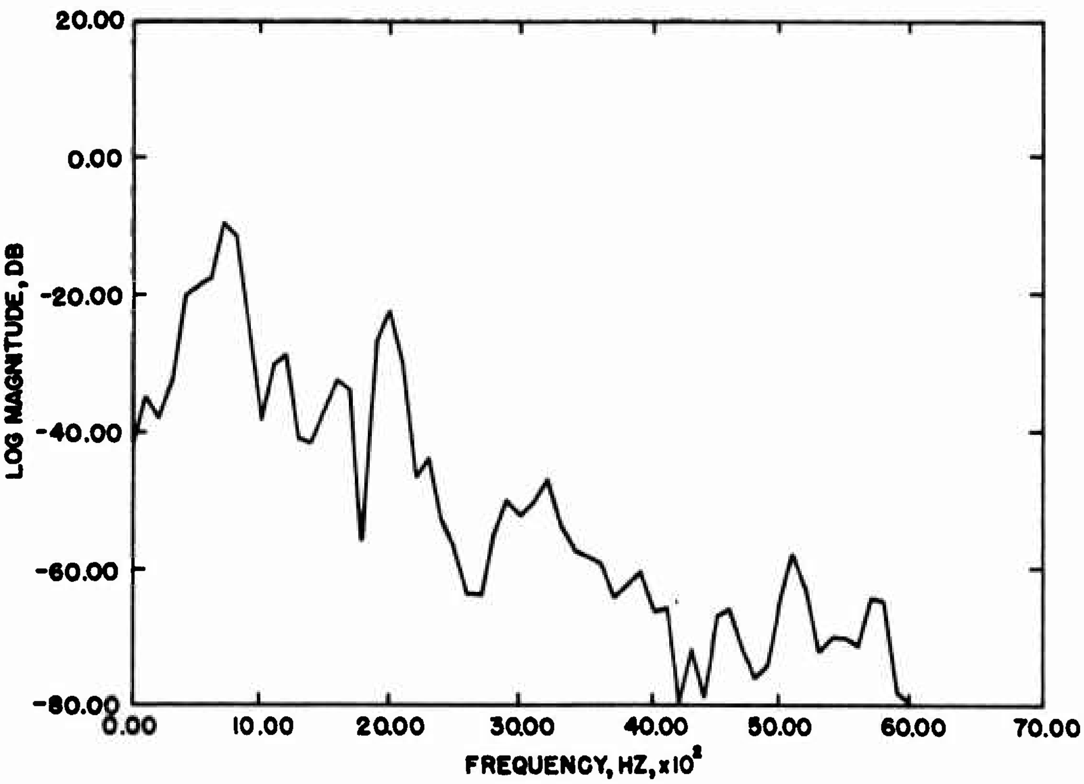


Figure 17. Frequency spectrum of figure 16.

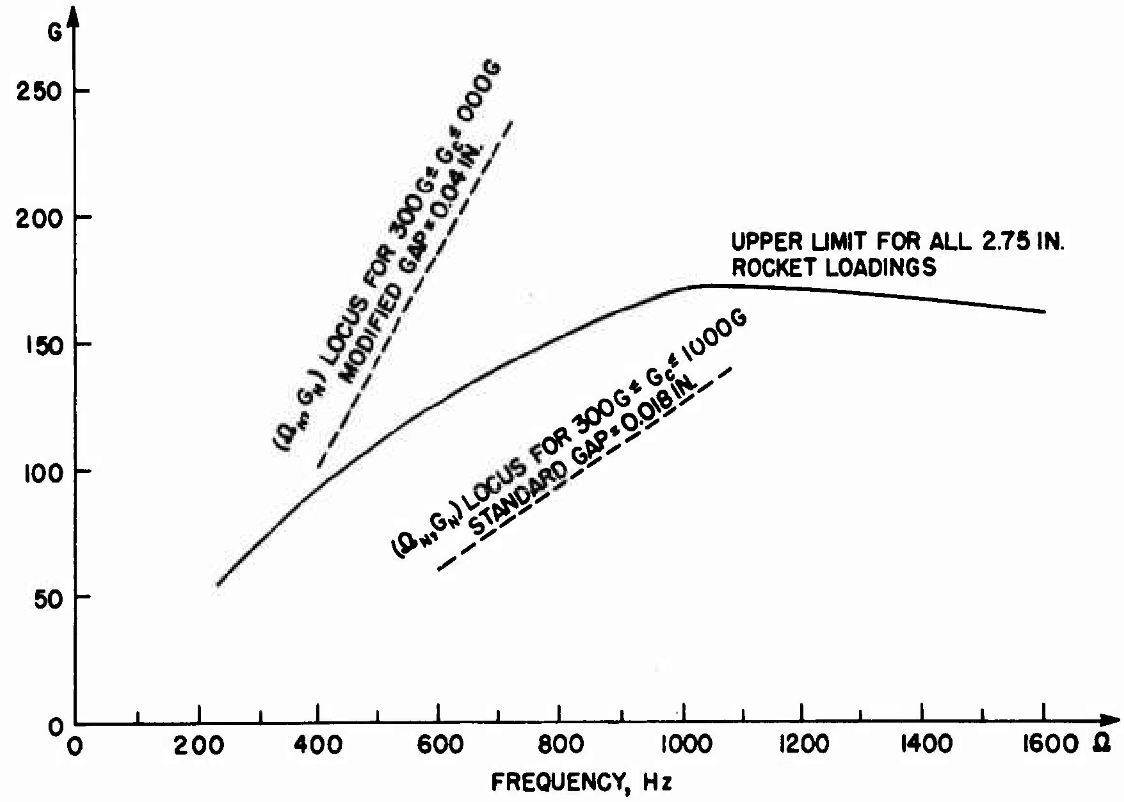


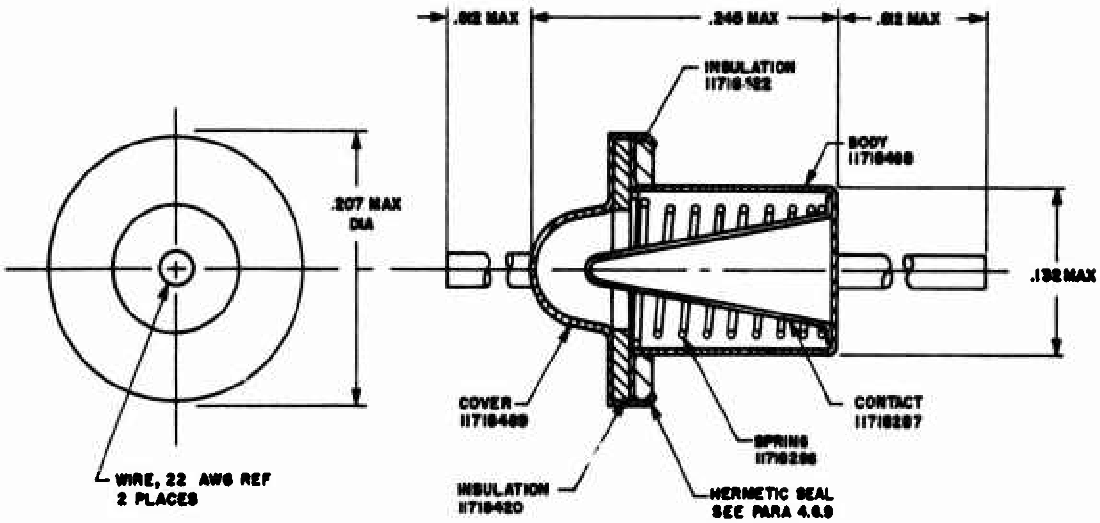
Figure 18. Comparison of the rocket loadings to the sensitivities of a switch with two different gap sizes but with the same manufacturing tolerances.

5. LIMITATIONS

Admittedly, there are many features associated with an exact analysis that have been omitted in the text. These features include duration of loading, realities of the $(G_t)_{max}$ calculations in terms of stress in the rocket and fin, significant calculations in terms of the magnitudes of vibrations down range from the launch site, the tolerances on the calculations due to rocket-to-rocket variations, the effects of fin damage, and the effects of modulations in frequency and G level during flight on the stability of the nonlinear switch. These rigorous aspects of the analysis are omitted because the circumstantial evidence is sufficient to warrant a precautionary engineering change in the impact switch.

6. RECOMMENDATIONS

Two changes are possible. One change would be to redesign the switch with a 0.04-in. gap; then, modify the specifications to raise the centrifuge G_c minimum from 300 to 450 G, and the vibration table G_n minimum from 60 to 100 G, and rewrite the acceptance provisions in the specifications. The second change would be to replace the Skinny switch in the FMU-98 drawing package with the Low-Cost switch (fig. 19). This latter approach is recommended, based on the following reasons:



NOTES:
1. MIL-A-2550 APPLIES.
2. IMPACT SWITCH SHALL MEET THE REQUIREMENTS OF SPECIFICATION CONTROL DRAWING, 11718418.

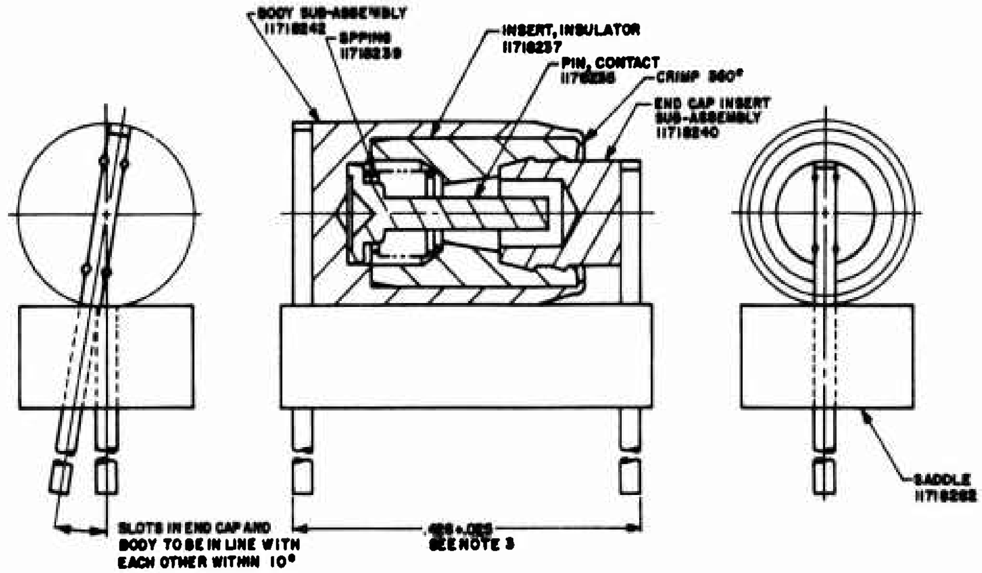
Figure 19. Low-Cost switch used in the XM734 mortar fuze (300 G) and the M728 artillery fuze (300 G). (Spec control drwg #11718418)

(1) The gap size of the Low-Cost switch cannot be altered by handling. The specifications also include typical thermomechanical handling loadings in the acceptance testing.

(2) Table II shows that the Low-Cost switch tested with a detonator in the circuit is more resistant to vibrational loading than the Skinny or Fat switches (fig. 20).

(3) The Low-Cost switch is small, which may allow it to be mounted in the fuze along the polar axis or else a line that is skewed from the geometric radial. This will reduce the effect of tangential, torsional accelerations.

(4) Acceptance testing is specified under end-use conditions. The lack of these definitions in the specifications for the Fat and Skinny switches has led to the improper construction of an electronic latching circuit to detect closure. The data in table II prove this contention. The Fat and Skinny switches were selected as control samples for detonator tests after 100-percent testing with the electronic latching circuit. Under detonator testing, the failure rate of the Fat switches at 40 G is high and certainly not within the acceptable quality level defined in the specifications. The Skinny switches all functioned above 100 G and the acceptable level is 60 G. Thus, the switches performed as designed, but, since the same circuitry is used to detect closures in production, Skinny switches could be stockpiled with undetected distorted gaps.



NOTES:

1. MIL-A-2550 APPLIES.
2. IMPACT SWITCH ASSY SHALL MEET THE REQUIREMENTS OF SPEC CONT DWG NO 11718231.
3. THESE DIMENSIONS SHALL NOT INCLUDE SOLDER. A SOLDER BUILD UP OF .020 MAXIMUM IS PERMISSIBLE ON EACH END.

Figure 20. Fat switch used in the XM732 artillery fuze (300 G). (Spec control drwg # 11718231.)

TABLE II. VIBRATION-TABLE DATA

Testing company (dates)	Switch type manufacturer	Design ratings $\sim G_c/G_n$	No. switches	No. closures/ No. tests	Vibration table (G)	Predominant firing frequency (Hz)
Brown						
(5/22-25/72)	Skinny/Gibbs	600/60	50	52/100	125**	180**
(1/23/73)	Low Cost/Kaupp	600/100	100	23/300*	125	450
	Fat/Gibbs	300/40	50	54/100	40	180,450
	Low Cost/Kaupp	300/40	100	8/200	40	450
Continental	Fat/Gibbs	300/40	38	11/76	40	---
(9/4/73)	Low Cost/Kaupp	300/40	152	0/304	40	---

*Each sample was tested at room temperature in two directions perpendicular to the longitudinal axis except the second row of the Brown tests. Of these 300 tests conducted by Brown, 50 switches were subjected at room temperature, another 50 switches were tested at both high and low temperatures.

**These mostly functioned below 100 G as the vibration table was being brought up to the specified 125 G. Perturbations in the frequency and G (observed on the vibration table chart recording) probably account for the low firing frequency. Note that the applied G is well above the design rating for the switch.

The specification pages for all types of switches shown in table II should be modified from the slow-sweep vibration table testing to tests that include modulations in frequency and G. This is to account for the fact that the switches are nonlinear and experience unstable, unpredictable jump phenomena that affect the dynamic response.

The disadvantages associated with using the Low-Cost switch in the FMU-98 fuze are that the field experience is limited, the dead zone is larger, and equations that describe the dynamic response have not been derived.

7. SUMMARY AND CONCLUSIONS

The FMU-98 fuze experienced an early function during a field test on the 2.75-in. rocket. The timing of the event focused attention on the inertial impact switch. In-flight vibration data obtained from a test rocket showed mechanical forcing functions may have existed during the time considered. These were attributed to rattling of the fins and sputtering of the motor. The loadings of greatest concern were tangential accelerations due to torsional oscillations of the rocket. The reasons were that the direction of loading was in the most sensitive plane of the switch, and the magnitude of loading was several orders larger than axial or flexural accelerations. For the sake of a worst-case analysis, the data taken from a radially mounted accelerometer were assumed to be due to torsion only, and these were used to calculate the frequency and G magnitudes associated with tangential accelerations. A comparison of the estimated rocket loadings to calculations of the normal range of dynamic responses expected from production switches showed the switch design to be marginal unless the gap size was increased. However, the gap size desired requires a major redesign of the switch, and the lack of structural integrity leaves the gap size continuously in doubt.

The recommendations include that: (1) the 600-G Skinny switch in the FMU-98 drawing package be replaced with a 600-G Low-Cost switch; (2) the centrifuge rating be $450\ G \leq G_c \leq 1000\ G$; (3) the vibration-table rating be $G_n = 100\ G$; (4) the switch mounting be on the polar axis of the fuze or skewed from a geometric radius in the fuze; and (5) a random vibration test be defined for acceptance purposes.

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