PYROTECHNIC SHOCK FLIGHT FAILURES*

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OBJECTIVE

The objective of this paper is to present "lessons learned" regarding the potential for pyrotechnic shock to induce flight failures. In addition, it is desired to place pyrotechnic shock environments in perspective relative to other dynamic environments normally considered in the design and testing of space vehicle equipment.

INTRODUCTION

In the early 1960's, a missile flight test failed catastrophically at launch when relay contacts in the safety destruct system inadvertently closed due to shock from launch release explosive bolts. Two years later, a second generation ICBM experienced a similar failure. Beginning with these early experiences, a file of flight failures due to shock and vibration has been maintained by the author. These data show many failures due to pyrotechnic shock and very few due to vibration. Data from these files, which are contained in this paper, were originally presented on 1 October 1982 at a pyrotechnic shock seminar sponsored by the Orange County California Chapter of the Institute of Environmental Sciences, (Ref. 1). In late October 1982, the same presentation was made at the annual meeting of the Shock and Vibration Information Center held in Boston, Massachusetts, (Ref. 2). As a result of presentations at these two meetings, a large amount of additional data regarding flight failures attributed to pyrotechnic shock were made available. These additional data were volunteered from files of dynamics engineers working for major contractors and also for The Aerospace Corporation.

DISCUSSION

This paper discusses a total of 85 flight failures where pyrotechnic shock was either the proven cause or was highly suspected to be a contributing cause of the failure. Table l provides a summary of the flight failures due to shock from 14 different programs labeled A through N. The programs are designated and listed to chronological order. Flight tests for Programs A, B, and C occurred in the early 1960's and for Programs K, L, M, and N in the mid-1970's. The last failure included in the available data bank occurred in 1977. A large majority of these failures occurred on missiles and space boosters; only one failure is from orbiting space vehicles. Among the same programs, three vibration-induced failures have been identified. The vibration-induced failures are summarized in Table 2.

Identification of the cause of flight failures generally requires considerable investigative work, usually with little data to support a clear cause and effect relationship. In only a few cases has the failed equipment been recovered to aid in proving the cause of the failure. On launch vehicles, flight failures attributed to pyrotechnic shock or vibration are more easily identified in terms of their cause and effect relationship than those which occur on orbit in space vehicles. This is due to the discrete nature of the shock and vibration environment and the fact that electronic equipment is in powered-up, functional state during the environmental exposure. This is not the case for most orbital vehicle equipment; therefore, identification of the cause of failure of an equipment item which is failed when turned on at orbit is much more difficult. For these reasons, the best failure data base to use in order to evaluate shock and vibration-induced failures must come from experience with launch vehicles. However, there are certain shock failure modes, such as relay chatter which, although catastrophic for launch vehicles, may not be critical for an orbiting spacecraft.

Of the 85 failures listed in Table 1, 19 occurred within a few msec of a major shock generating event. In these cases, coincidence of the failure with the shock event gave the first strong clue of the cause. The failure analyses are usually performed using telemetry data which allow the failure to be traced to a specific component in an electrical circuit. For example, Program K had a guidance system failure which occurred 280 msec after a booster staging shock event. Through analysis of telemetry data, electrical circuit analysis, and subsequent system testing, the most probable cause of the failure was traced to particle contamination within a power transistor of the Inertial Measurement Unit. The remaining 66 failures of Table 1 occurred from 3 to 100 sec after the major pyrotechnic shock event. Of these remaining failures, 22 were also diagnosed as highly likely to have been caused by shock. In all cases, corrective actions taken by the programs were consistent with a shock-induced failure. Subsequent flight experience was successful giving further credence to the shock failure diagnoses. Therefore, in 41 (19 + 22) of the 85 failures summarized, there is a high degree of confidence in concluding that the failures were caused by shock.

The remaining 44 failures listed in Table 1 are considered to have a better than 50% probability that shock was either the direct or a contributing cause of the failure. This is the author's assumption, based on the reasoning that none had occurred earlier in the flights during the periods of highest vibration; however, all failures occurred within a short time after significant shock events and during times of relatively benign thermal and vibration environments. If it is assumed that 50% (22) of these were due to the shock environment, the total number of shock-induced failures is approximately 63.

Before the flight failures are reviewed in more detail, it is of interest to review failures which have occurred during ground pyrotechnic shock testing. Table 3 shows various classes of failures which have been recorded during ground testing. Every class of shock-induced failure shown in Table 1 has also occurred during flight. The following discussion categorizes the flight failure information in Table 1 by class of failure similar to those shown in Table 3.

* This study was supported by the Space Division, Air Force Space Command under Contract No. F04701-83-C-0084.

Table 3. Failures During Ground Pyrotechnic Shock Testing

- RELAYS AND SWITCHES
  - CHATTER AND TRANSFER
  - PERMANENT DAMAGE
- CRYSTALS, CERAMICS, BRITTLE EPOXIES, GLASS DIODES, WIRE LEADS
  - CRACKS AND BREAKAGE
  - LOSS OF SEALS
  - BOND FRACTURES
  - SHORTS
- PARTICLE CONTAMINANTS IN PIECE PARTS
- DEFORMATION OF SMALL LIGHT WEIGHT STRUCTURAL ELEMENTS

RELAY CHATTER/TRANSFER

This class of failure occurred four times, once each on Program A, D, G and H. In each case, the failure caused catastrophic loss of the mission. Shock levels causing these failures ranged from 600 to 4000 g's peak of the shock response spectrum at frequencies greater than 2000 Hz. Design and testing deficiencies which allowed these failures were very similar in all cases.

The shock environments were not well-understood or defined, as system level shock tests had not been performed. The components containing relays were qualified to shock levels much below flight levels. Two examples are: (a) a component qualified to 160 g peak spectrum while flight shock was greater than 2000 g peak spectrum and (b) a component qualified to 60 g peak spectrum, whereas flight shock was 1100 g peak spectrum. In each of these cases, the relay contacts were part of powered-up electrical subsystems which would not tolerate either relay contact transfer or chatter. The failure resolution or fix that was implemented for each of the four cases involved (as a first step) performance of a system level test to define the shock environment. Then the component was either ruggedized or protected from the environment by shock isolation or by relocation to an area of lower shock.

Several of the programs listed in Table 1 make it standard design practice to shock isolate relays by encasing them in foam. Although programs utilizing this design practice have experienced a number of shock-induced flight failures, none have been related to relay chatter or transfer. This would be good design practice for any program where relay chatter during shock could be detrimental.

BROKEN ELECTRICAL WIRES LEADS, CRACKED GLASS

This type of failure, defined as a hard failure, occurred a total of approximately 30 times among Programs B, C, F, I, M, and N. In 17 cases, the failure caused catastrophic mission loss, and in 13 cases it resulted is mission degradation. Shock levels causing these failures were always relatively high–3000 g response spectrum peak or more at frequencies greater than 2000 Hz. The significance of this is discussed in more detail later. In addition to high shock levels, the components (in many cases) were not adequately qualified, and the magnitude of the shock had not been determined by system level testing. Corrective actions that were taken to eliminate this type of failure included performance of shock system level tests to define the shock, components mounted on shock isolators, and redesigned and requalified components. Program M, which had five catastrophic flight failures due to the hard failure type of problem, took several corrective actions. Most components were placed on shock isolators. Component shock qualification levels were increased to assure a positive margin above maximum flight levels. The component acceptance test program was expanded to include shock testing of the most complicated or shock-sensitive units. By the time that these corrective measures were adopted on program M, there have been no electronic box failures during subsequent flight tests.

Information regarding shock levels associated with failures discussed in this paper was available only in terms of the maximum shock spectrum value at frequencies above 2000 Hz. In the case of hard failures such as wire and lead breakage, all failures were due to shock spectrum levels greater than 3000 g above 2000 Hz. In a general way, equipment shock acceleration fragility limits would be expected to have a tendency to be inversely related to frequency because of the inverse relationship between displacement and frequency in vibrating systems. MIL-STD-810D (Ref. 3) contains guidelines reflecting an inverse relationship between equipment shock acceleration fragility limits and frequency. MIL-STD-810D states that shock spectrum g levels below values of 1.6 times frequency in Hz tend not to cause failures in military-quality equipment. Comparing this guideline with the g levels which caused the hard failures reported in this paper shows good agreement; i.e., 1.6 times a frequency of 2000 Hz equals 3200 g versus 3000 g at frequencies of 2000 Hz or greater. MIL-STD-810D recommends that tests be conducted if the actual expected shock spectrum g values are greater than 0.8 times frequency in Hz. The types of hard failures which have occurred in flight can be related to either design or workmanship defects. For this reason, it appears that shock acceptance and qualification tests are very desirable when spectrum g levels exceed the guideline of 0.8 times frequency in Hz.

DISLODGING OF CONTAMINANTS IN PIECE PARTS

This type of failure occurs when a shock event liberates conductive particle contaminants within piece part cavities, and the conductive particles cause short circuits. These failures generally have not occurred coincident with the shock event; thus, it has been more difficult to establish a cause and effect relationship. At least 29 of the flight failures listed in Table 1 are believed to have been caused by shock events which jarred conductive particles loose; the particles then migrated to and caused shorts in microcircuits. In 24 cases, the failure resulted in catastrophic loss of mission and, in one case, mission degradation; four cases are unknown. This failure mechanism has occurred at very low, as well as very high, shock levels. Program L had a flight failure caused by a shock level of only 200 g peak response.

A single design improvement which has greatly reduced the occurrence of the loosened contaminant type of failure on most programs has been passivation of cavity-type piece parts. Passivation is accomplished by coating microcircuit elements with a dielectric such as glass. This helps to trap particles and reduces the likelihood of short circuits. A study performed as a result of flight failures on Program J showed approximately a 20:1 improvement in failure rate for passivated versus non-passivated parts.

Other corrective actions taken to reduce the probability of this type of failure were improved screening tests at the piece part and component level of assembly. Piece-part screening has included Particle Impact Detection (PIND) tests. The effectiveness of PIND testing as a means of screening out piece parts that contain contaminants appears to be is the range of 30 to 50% (see Ref. 4). Component screening tests imposed to resolve the contamination type of problems have generally been a combination of shock and vibration. Programs J, K, L, and M instituted component screening tests including shock followed by vibration with electrical circuits energized and monitored. Generally, the vibration has been applied twice in each axis with the component inverted for the second test to increase the probability that gravity would move the particles to an area of the circuit where they would be detected. Programs K, L, and M which had contamination-type failures have reported no further flight failures since incorporating shock and vibration screening, along with other improvements in their component acceptance test program.

DEFORMATION OF SMALL, LIGHTWEIGHT STRUCTURAL ELEMENTS

Failure of structural elements due to pyrotechnic shock is rare. Occasionally, brackets such as those supporting electrical connectors and located very near to explosive ordnance devices have bent or, in one case, fractured during ground pyrotechnic shock tests. No flight failures of this type are contained in Table 1. However, a failure of this general type appears to have occurred in 1971 with the USSR Soyuz 11, resulting in the loss of lives of three cosmonauts.

Quoting from the Los Angeles Times, 29 October 1973:

"Washington - The three Soviet cosmonauts who died in earth orbit two years ago were killed when all the air in their Soyuz spacecraft rushed out through an exhaust valve that had accidentally been triggered open. The valve in the Soyuz 11 cabin tripped open just after the cosmonauts had separated their reentry capsule free from the large orbiting capsule, a maneuver in which it was necessary to fire 12 explosive bolts that connected the two spacecraft. The shock of the firing apparently forced the valve open and loosened a valve cap that acted as a safety device."

The above information was provided to U.S. space officials in preparation for the joint Apollo-Soyuz docking mission.

POTENTIAL SHOCK FAILURES WHICH HAVE OCCURRED ON SPACECRAFT

As stated earlier, the last clearly identified shock failure occurred in 1977. This suggests that the aerospace industry has learned how to prevent and has eliminated shock-induced failures. The failures reported herein, however, are almost entirely the experience of launch vehicles where cause and effect relationships are more easily established. The only new expendable launch vehicles built since 1977 are later generation versions of prior vehicles built by the same contractors. Clearly, it seems that the launch vehicle part of the industry has learned how to prevent shock-induced failures.

In an attempt to assess potential shock-induced failures in previously launched space- craft, a review of a failure data bank, "Orbital Data Analysis Program (ODAP)," maintained for spacecraft was performed. The available data bank included failures recorded for 128 spacecraft. In nearly all cases, spacecraft equipment was unpowered during most shock events with power applied only after orbit was reached. The ODAP data records segregated failures by blocks of time in which they occurred. The first block of time in which failures were categorized began with launch and ended after five days in orbit. Nearly all shock events occurred within this period. Sometimes the failure analysis summary contained a statement that the component was found to be failed when it did not turn on during early orbital activation. Review of these data identified 72 failures which were potentially shock-related. Screening criteria used to identify potential shock failures were as follows:

a. The failure analysis team concluded the failure to be potentially shock related.

b. The failure cause was stated as unknown, and it was of the type which has occurred on launch vehicles. Excluded were those which contained information indicating that the failure occurred well after orbit was reached.

Most of the failures did not have a catastrophic effect on the mission, mainly because of redundant systems. Based on the number of spacecraft failures which could potentially be shock-related and the poor experience of launch vehicle programs, it appears that lessons learned on launch vehicle programs should be applied to spacecraft progress. The launch vehicle experience is, for the most part, considered applicable to orbital spacecraft programs. Spacecraft designs in general are somewhat less sensitive to some types of shock-induced failures. For example, relay contact chatter or transfer is more likely to be tolerable in spacecraft equipment during shock events than it is in boost vehicle systems. A transferred relay in a spacecraft usually can be reset with no significant harm to the vehicle. The hard failures including wire breakage and cracked glass or the piece part contamination failures which form a majority of the failures reported herein would present a significant concern for most spacecraft designs.

COMPARISONS OF SHOCK VERSUS VIBRATION FAILURES

In contrast to the large number of shock-induced failures, only three vibration-induced failures have occurred among the same progress listed in Table 1. A summary of vibration-induced failures is shown in Table 3. Based on the data in this paper, the ratio of shock to vibration failures is in excess of 41:3 or 14:1. The reason for this high ratio of shock versus vibration failures is of great interest to personnel involved in planning and conduct of acceptance and qualification test programs for space vehicle equipment. Apparently, there are two major reasons for the unacceptably high number of shock failures:

a. In the period during which the repotted failures occurred (1960 to 1977), the technical understanding of shock environments and their effect on equipment lagged behind vibration technology by an estimated 10 years. In early years of the aerospace industry, few engineers recognized the damage potential of shock on electronic equipment. Some engineers believed that a rigorous vibration test of several minutes duration would surface failure modes that could occur as a result of a typical 10 to 20 msec duration pyrotechnic shock environment. The error in this assumption is shown in Fig. 1 where a comparison is made of typical shock and vibration specifications for space vehicle equipment. In Fig. 1 the vibration specification has been translated to a response spectrum for comparison with the shock specification. This comparison shows that at all frequencies above approximately 150 Hz, the peak shock accelerations are much higher than the vibration accelerations. Failure mechanisms caused by peak shock accelerations therefore would not be detected by the lower amplitude vibration.

b. Vibration test requirements have been conservative, well-defined, and almost universally applied since the early 1960's. Shock test requirements have generally not been applied with the same degree of thoroughness. For example, acceptance and qualification vibration testing is almost universally performed on all space vehicle equipment at various levels of assembly before launch. Past practice has generally not included shock as a part of component acceptance testing. However, Programs K and M shown in Table 1 instituted shock acceptance testing of components after the reported flight failures. Also, component shock qualification testing has not been universally performed in the past nor is it at the present time.

SUMMARY AND LESSONS LEARNED FROM FLIGHT EXPERIENCE

The number of flight failures induced by pyrotechnic shock in launch vehicles is exceptionally high – at least 41 but more likely in excess of 60. This is at least 14 times greater than the number of failures due to vibrations. Approximately 70% of the shock failures resulted in catastrophic loss of the mission. Improvements in electronic equipment designs (primarily passivation of piece parts) and establishment of rigorous testing practices have greatly reduced the occurrence of shock failures in launch vehicles. The last clearly identified shock failure of a launch vehicle occurred in 1977. In space vehicle programs, cause and effect relationship between shock or vibration and a failure is difficult to establish. Equipment is often unpowered when these environments occur; thus, failure is not detectable until equipment is powered up. However, a survey of failures which occurred during flight of 128 spacecraft shows a significant number which may have been shock-induced. The lessons learned in launch vehicle programs appear to be generally applicable to space vehicle progress. The following recommendations are based on experience of the programs discussed in this paper. The recommendations are considered to apply to launch and space vehicle programs.

- System level shock tests should always be performed. The vehicle should be well-instrumented to measure shock, and all ordnance should be activated.
- if possible, non-passivated piece parts should be avoided. They can be susceptible to shock-induced failure at relatively low shock levels. If non-passivated piece parts must be used, they should be subjected to PIND screening tests.
- Shock and vibration acceptance screening tests of components are recommended when either of the following conditions exist: (a) when non-passivated piece parts are used in the component, or (b) when flight shock spectrum g levels exceed 0.8 times frequency in Hz.
- Space vehicle design activities should have the goal of minimizing shock levels at electronic components. This can be accomplished by use of shock isolators, use of low shock ordnance devices, location of equipment away from shock sources, or use of structural configurations which have poor transmissibility of shock, e.g., structural discontinuities.
- Electronic and electromechanical equipment should always be qualification tested. Qualification test margins specified in MIL-STD-1540B (Ref. 5) are recommended.
- Shock isolation of relays is recommended for those cases in which chatter or transfer of relay contacts during shock event can have a detrimental effect on electrical subsystems.

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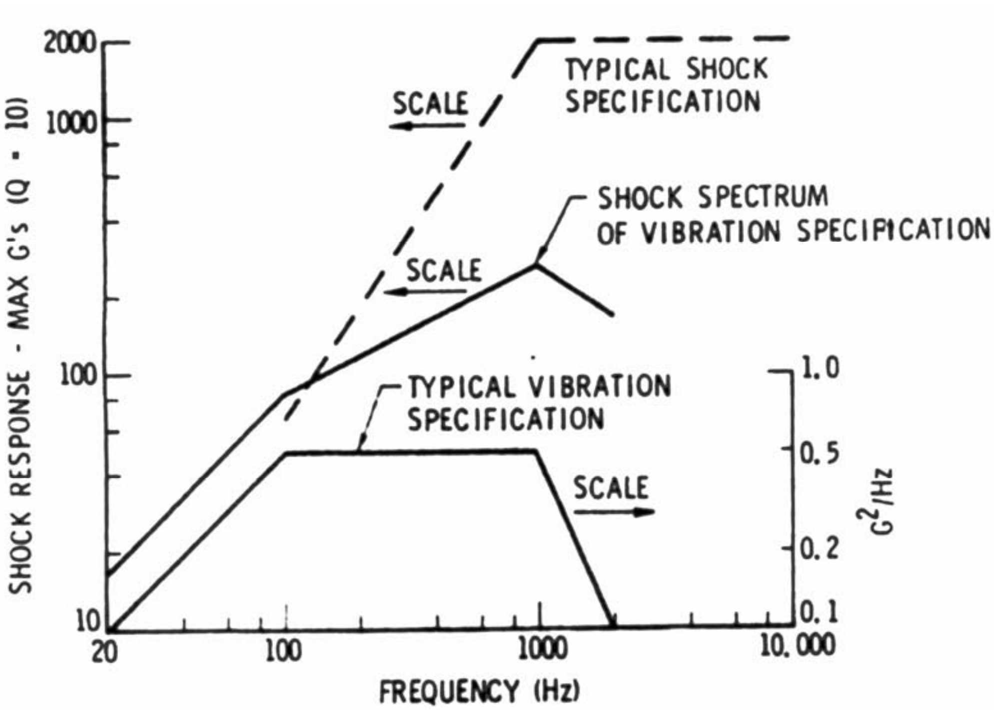

Figure 1. Pyrotechnic Shock versus Vibration Levels

Table 1. Summary of Flight Failures Associated with Pyrotechnic Shock

PROGRAM	NO. OF FAILURES/ NO. LIKELY SHOCK INDUCED	FAILURE TYPE	ESTIMATED PEAK SHOCK SPECTRUM (g's)(100-10,000 Hz)	TIME OF FAILURE AND MISSION EFFECT	FIXES
A	1/1	• RELAY TRANSFER	4000	• COINCIDENT WITH SHOCK • CATASTROPHIC	• RELOCATE COMPONENT CONTAINING RELAYS
B	17/8	• ELECTRONIC BOX FAILURES • PIECE PART CONTAMINATION (8) • UNKNOWN(9)	3000	• 5 TO 100 SEC AFTER SHOCK • ALL CATASTROPHIC	• SHOCK ISOLATION • PASSIVATE PIECE PARTS
C	16/16	• ELCTRICAL SHORTS • BROKEN WIRES	3000	• SHORTLY AFTER SHOCK • 3 CATASTROPHIC • 11 DEGRADED PERFORMANCE	• SHOCK ISOLATION
D	1/1	• RELAY TRANSFER	UNAVAIL.	• COINCIDENT WITH SHOCK • CATASTROPHIC	• RELOCATE COMPONENT CONTAINING RELAYS
E	1/1	• PIECE PART CONTAMINATION	2800	• SHORTLY AFTER SHOCK • CATASTROPHIC	• IMPROVED SCREENING
F	1/1	• BROKEN WIRE	6000	• COINCIDENT WITH SHOCK • DEGRADED PERFORMANCE	• REDESIGN TO REDUCE SHOCK LEVEL
G	1/1	• RELAY TRANSFER	1400	• COINCIDENT WITH SHOCK • CATASTROPHIC	• SHOCK ISOLATION
H	1/1	• RELAY CHATTER	600	• COINCIDENT WITH SHOCK • CATASTROPHIC	• UNAVAILABLE
I	24/16	• ELECTRONIC PACKAGE FAILURES (7) • PIECE PART CONTAMINATION (9) • UNKNOWN (8)	3100	• 7 COINCIDENT WITH SHOCK • 17 AFTER SHOCK (3 TO 90 SEC) • ALL	• SHOCK ISOLATION • PASSIVATE PIECE PARTS • IMPROVED SCREENING
J	4/4	• PIECE PART CONTAMINATION • MECHANICAL FAILURE OF DIE	UNAVAIL.	• AFTER SHOCK • UNAVAILABLE	• IMPROVED SCREENING
K	1/1	• PIECE PART CONTAMINATION	1500	• COINCIDENT WITH SHOCK • CATASTROPHIC	• PASSIVATE PIECE PARTS • ACCEPTANCE SHOCK TESTING • IMPROVED SCREENING
L	1/1	• PIECE PART CONTAMINATION	200	• SHORTLY AFTER SHOCK • CATASTROPHIC	• IMPROVED ACCEPTANCE TESTING
M	15/10	• ELECTRONIC PACKAGE FAILURES (5) • PIECE PART CONTAMINATION (5) • UNKNOWN (5)	3000	• 5 COINCIDENT WITH SHOCK • 10 AFTER SHOCK (5 TO 100 SEC) • ALL CATASTROPHIC	• SHOCK ISOLATION • PASSIVATE PIECE PARTS • ACCEPTANCE SHOCK TESTING • IMPROVED SCREENING
N	1/1	• BLOWN FUSE	UNAVAIL.	• COINCIDENT WITH SHOCK • DEGRADED PERFORMANCE	• UNAVAILABLE

Table 2. Summary of Flight Failures Attributed to Vibration

PROGRAM	NO. OF FAILURES	FAILURE TYPE	ESTIMATED OVERALL g_{rms} (20-2000 Hz)	TIME OF FAILURE MISSION EFFECT
B	1	• ELECTRONIC BOX FAILURE	UNKNOWN	• COINCIDENT WITH HIGH VIBRATION LEVEL
F	1	• ELECTRONIC BOX FAILURE	20	• COINCIDENT WITH HIGH VIBRATION LEVEL • CATASTROPHIC
	1	• COMPONENT FAILURE	UNKNOWN	• COINCIDENT WITH HIGH VIBRATION LEVEL