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Pyrotechnic System Failures: Causes and Prevention

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PREFACE

This paper was motivated by an early 1986 expression of concern about recent problems and failures of flight pyrotechnic hardware by Norman R. Schulze, NASA Headquarters, then Office of the Chief Engineer, and now Office of Safety, Reliability, Maintainability and Quality Assurance. The Langley Research Center (LaRC) was requested to take the lead role in compiling an investigation about the extent of this problem and to explore the technical understanding of the field of pyrotechnic technology. The emphasis on this effort is substantiated by the overall assumption in the design community that pyrotechnics are simple, well-defined and thoroughly understood devices to which we routinely entrust mission-critical as well as safety-of-flight functions. The first action was a May 15, 1986, NASA/DOD survey from Langley entitled, "Solicitation of Interest in a Coordinated Pyrotechnic Technology Effort Among Centers." Two meetings followed, one on November 13 and 14, 1986, at the NASA Langley Research Center, and the other on April 29 and 30, 1987, at the NASA Johnson Space Center, with representatives from each NASA Center, the Air Force Space Division, and the Naval Surface Warfare Center. These representatives are now the nucleus of the NASA/DOD Aerospace Pyrotechnic Systems Steering Committee, whose objective is to provide the NASA and DOD with a policy and posture which will increase the safety, performance, quality and reliability of aerospace pyrotechnic systems.

The NASA/DOD Aerospace Pyrotechnic Systems Steering Committee has been the primary source of information for the compilation of failures presented in this paper, and the members have participated in the data analysis and final review of this report. The thoroughness and traceability of the failures presented herein are not germaine to this study, since only an indication of pyrotechnic problems was sought.

SUMMARY

Although pyrotechnics have successfully served a critical role in accomplishing spacecraft mechanical functions, failures continue to occur. Recent occurrences prompted Norman R. Schulze, NASA Headquarters, to initiate a survey to determine the frequency and cause. This paper describes a survey compiled for a 23-year period which includes 84 serious component or system failures, 12 occurred in flight, with fully developed and qualified hardware. Analyses are presented as to when and where these failures occurred, their technical source or cause, followed by the reasons why and how these kinds of failures continue to occur. The results of these efforts frequently indicated a fundamental lack of understanding of the functional mechanisms of pyrotechnic devices and systems, followed by not recognizing pyrotechnics as an engineering technology, insufficient manpower with "hands-on" experience which has led to a heavy dependence on manufacturers, too few in-house test facilities, and inadequate guidelines and specifications for design, development, qualification and acceptance. Recommendations are made on both a managerial and technical basis to prevent continued pyrotechnic system failures, increase reliability, improve existing and future designs, and develop the technology to meet future requirements.

INTRODUCTION

Pyrotechnics, as a term used herein, comprise both explosive and propellant-actuated mechanisms, but exclude propulsion. Pyrotechnics have accomplished a large number of the mechanical functions for space missions, including 24 for Apollo, and while extremely high reliability has been demonstrated in both manned and unmanned applications, nagging system failures continue to occur. These failures have caused three deaths and have resulted in considerable expense in redesign, requalification, repeat of system tests, and flight delays, as well as the less definable losses in morale and prestige through experiencing flight failures.

Norman R. Schulze of the Office of Associate Administrator for Safety, Reliability, Maintainability and Quality Assurance, concerned about the short- and long-term management of pyrotechnic failures, recognized that inter-Center coordination could be the most effective approach to defining, understanding, and reducing these failures. The potential benefits of inter-Center coordination were demonstrated by two highly successful programs under his management: the "NASA Aerospace Flight Battery Systems Program" and the "Shuttle/Centaur Super*Zip Separation Joint Failure Analysis and Resolution Program". Reference 1 provides a summary of the battery experience, and reference 2 provides a description of the Super*Zip technical resolution. Both of these programs addressed existing complex problems and failures with multiple causes. A resolution to the Super*Zip failure was achieved in real time with active participation by every NASA Center, as well as the Air Force and Navy and four industrial users, to immediately implement improvements in existing flight systems. The efficient inter-Center coordination resulted in the creation of the NASA/DOD Aerospace Pyrotechnic Systems Steering Committee, composed of leading pyrotechnic technologists from the NASA Centers, the Space Division, Air Force Systems Command, and the Naval Surface Warfare Center (table I).

The need to determine the extent of problems in the pyrotechnic community became the obvious first activity of the steering committee. Each of the committee members supplied failure information and lessons learned to be used for the following specific objectives of this paper:

1. Provide a compilation of pyrotechnic failures, including program impact, sources of failures, and resolutions.
2. Analyze the past failures to determine when they occurred in the use cycle and the basic causes for occurrences.

3. Consider specific pyrotechnic technology deficiencies that allowed failures to occur.

4. Recommend technical and managerial approaches to:

    a. Increase reliability through failure prevention
    b. Provide the theoretical and practical basis for the understanding of pyrotechnic functional mechanisms.
    c. Improve existing designs and provide improved design approaches and specifications as the technology base expands.
    d. Develop the technology to meet future requirements.

PROCEDURES FOR FAILURE SURVEY AND ANALYSIS

This section describes the approach used in conducting the pyrotechnic failure survey and the subsequent analysis to provide direction for the final recommendations.

Survey Approach

The intent of this failure survey was to develop an insight into the extent of the problems in the pyrotechnic discipline, not to gain technical design information on the failures. Furthermore, to expedite the effort and reduce the time commitment by the committee sources (table I) the emphasis was placed on simplicity. Brief statements were requested on failures of hardware that was after design and was in qualification, system testing, lot acceptance testing, in the various phases of preflight preparations, flight, or in long-term storage, service life evaluation. Requested were the year of the failure, a brief description of the failure, the project impact, including the actual and potential if the failure mode had remained undetected, the source of the failure, and the failure resolution. Obviously, the project impact for each failure was an appreciable schedule delay and cost, so only statements of additional impacts beyond these were solicited. The failure source categories and their definitions are listed in table II, including specifications, procedures, quality control, design, technical understanding and misapplications. No requests were made for references or documentation on any of the failures.

Analysis Approach

The failures were grouped into several categories for analysis, then a subjective assessment was made to attempt to explain how and why these failures occurred. The failures were first categorized into pyrotechnic functions, and then were summed in terms of totals for (a) each functional category, (b) when they occurred in the life cycle of the device, and (c) the source or cause of each failure.

The functional categories were: initiation, defined as the first input into the device to start the functional train; mechanisms, mechanical devices used to accomplish a desired function; separation joints and linear explosives which are a type of device that can be applied in relatively long lengths to sever and release structure, such as rocket staging; and firing circuits, those electrical systems used to provide input energy to initiate pyrotechnic devices.

The "when the failures occurred" categories for devices with completed design were qualification, manufacture of the fully qualified device, lot acceptance testing, systems testing, flight assembly, flight and service life evaluation, or long-term storage. The "source or cause of failures" categories are listed in table II: Specifications, procedures, quality control, design, technical understanding and misapplications. For those failures with more than one failure category, only the primary cause was stated.

A subjective assessment was then made on the "state-of-the-art" of pyrotechnic technology that would explain why these failures occurred. Considered were: (a) recognition by the engineering community of pyrotechnics as a technical entity, (b) guidelines for design, development qualification, and testing, (c) communication, (d) sources of information, (e) reliance on manufacturers, (f) test facilities, (g) manpower, (h) training, (i) standards for requirements and hardware, (j) future requirements and (k) funding.

RESULTS

This section summarizes the results of the failure survey and the analysis of the compiled information.

Survey Compilation

The listing of failures is presented in tables III through VI under the categories of initiation, mechanisms, spacecraft separation joints and linear explosives and firing circuits. To better understand the presentation format, a more detailed description on representative examples for each category is given.

Initiation.- The most infamous pyrotechnic failure was the 1964 Delta program rocket motor ignition at Cape Kennedy that killed three people and injured eight. The filament-wound, fiberglass motor with assembled spacecraft was mounted in a vertical stand and covered with a protective plastic sheet. In rolling up the edges of the sheet to the top of the assembly to allow access to the spacecraft, thousands of volts of electrostatic energy were generated. These voltages caused an electrical breakdown through the initiation mix between the case and firing leads of an internally mounted squib (electrical initiator). The approach for electrostatic protection at that time was completely wrong. The resolution was to redesign the squib and igniter to reduce electrostatic energy sensitivity, as well as eliminate the possibility of achieving electrostatically generated voltages at sensitive locations.

The 1986 failure of the NASA Standard Initiator (NSI) to function in a -260° F lot acceptance test presents a major impact on a wide variety of spacecraft functions. Should the failure not be resolved, the use of the NSI may be restricted to special firing circuits or for use at warmer temperatures. For example, a dichotomy between operational environment and performance limitation is the Shuttle's hydrogen umbilical disconnect which must function at -420° F. The cause or source of failure is a lack of understanding of the materials and/or manufacturing controls necessary to achieve reliable initiation; test firings in samples of some few lots have all functioned, while the majority of lots have had functional failures. No failures can be tolerated.

Mechanisms.- The 1987 failure of two Magellan pin pullers has far greater potential impact than is initially apparent. This pin puller was the same unit fully qualified for the Viking Lander spacecraft for the 1976 landing on the surface of Mars. After this experience and with its pedigree, two units from a duplicate lot of pin pullers failed to function in a failure mode not recognized in the original design, development and qualification. First, the extremely dynamic pressure impulse output, as designed, of the NSI, when fired into a small eccentrically vented cavity was severely attenuated, reducing the energy available to stroke the piston. Furthermore, the bottom of the cavity was deformed by the pressure into a groove in the piston, which had to stroke to pull the pin. This device may have always been marginal when operated by a single cartridge input.

Spacecraft separation joints and linear explosives.- The 1983 and 1984 cold-temperature failures of the Shuttle/Centaur separation joint were caused by a lack of understanding of how the mechanism works. It was determined that the plates that were to be explosively fractured were too thick and too soft (reference 2). The critical thickness was not at the point of fracture, but at the points where bending occurred to introduce the dynamic stress at the point of fracture. To avoid stress corrosion sensitivity the plate material hardness was changed from earlier systems through annealing from a fracture-sensitive condition to a fracture-resistant condition. Although the joint was successfully severed in early demonstration tests despite this soft condition, a significant portion of the functional margin had been lost without the knowledge of system designers.

Firing circuits.- The 1987 launch pad lightning strike ignition of three of four sounding rockets was caused by electromagnetically induced energy in partially shielded and grounded firing leads. Facility hardware and procedures had been used successfully for over 30 years of launch operations. An unusual storm with sudden lightning identified the system weaknesses.

DATA ANALYSIS

This section describes the results of the failure survey in quantitative terms and provides a subjective assessment to help explain why the failures occurred.

Quantitative summary.- The total number of failures reported in this survey was 84. The frequency of occurrence for the 23-year period is shown in figure 1. The greatest number of failures occurred in 1984 with an average of 3.65 for the entire period. The flight failures are scattered throughout the period. The number of failures in each functional category is shown in figure 2. The number of failures in a device life cycle is shown in figure 3. Of course, the key statistic is that 12 flight failures occurred following qualification, lot acceptance testing, systems test and flight assembly. Figure 4 summarizes the pyrotechnic failure occurrences in terms of sources or causes.

Assessment on reasons for failures.- This section is a compilation of "state-of-the-art" opinions by the NASA/DOD Pyrotechnic Steering Committee as to how and why these failures occurred. These opinions are subdivided and presented in the following categories: pyrotechnic technology recognition, guidelines for design, development and qualification, communication, sources of information, reliance on manufacturers, test facilities, manpower, training, standards for requirements and hardware, future requirements and funding.

Pyrotechnic technology recognition.- Pyrotechnics have not been recognized as a separate and distinct technology, but have been relegated to a subsystem level of propulsion or structures. Even worse, pyrotechnic devices are considered analogous to "nuts and bolts", in that no fundamental engineering design is necessary; they need only be purchased and applied. Past edicts have shown the general opinion and the concern for pyrotechnic use, one of the more recent being, "Pyrotechnic applications are prohibited for both the Shuttle vehicle and Shuttle payloads." Other messages range from "Don't consider them, unless you have to," to "squibs are pretty reliable." Program managers generally have little background experience with pyrotechnic systems, or have heard horror stories of unexplained failures, and realizing the scarcity of experienced personnel, have avoided their use. In spite of these negative opinions, pyrotechnics do have their place in design applications for singular, non-repetitive functions that demand enormous amounts of directed energy in short periods of time.

Guidelines for design, development and qualification.- No standardized guidelines exist within NASA for pyrotechnic system design, development and qualification, as does the Air Force (reference 3). Development borders on magic and superstition. Subsequent failures leave the impression that pyrotechnics are dangerous, damaging, and at best, difficult to control. Some past pyrotechnic subsystem managers have actually conveyed to their program managers that no one can really understand how these devices work; they don't follow any known engineering laws. Since pyrotechnics are single-shot devices, past approaches for demonstrating reliability have relied heavily on developing a statistical verification without a clear understanding of functional mechanisms and the relative importance of system parameters. That is, once a successful performance was achieved, emphasis was placed on accomplishing large numbers of consecutive successes. (More than 2000 units are needed to establish a 99.99 percent reliability at a 95 percent confidence level.) However, the current approach often is to run full-scale systems tests on as few as six assemblies or less with no statistical guarantee of reliability, and without an adequate understanding of how the mechanisms function, a prescription for disaster.

Communication.- Most Centers work their pyrotechnic efforts independently with little intercommunication, cooperation or sharing of technical gains, problems, failures and resolutions. There has been little mutual participation among Centers in design reviews.

Sources of information.- No library or central source of information exists that is remotely oriented towards current aerospace pyrotechnic technology, particularly a databank on past failures. The failure survey in this paper was compiled primarily informally, on the basis of memory of the Steering Committee members. Few publications exist in this highly specialized area. Few programs thoroughly document and publish designs, functional performance and physical envelopes, particularly in a format permitting trade studies needed for new designs. The best pyrotechnic technology is in the minds of a handful of specialists with sufficient general experience to assess new applications.

Reliance on manufacturers.- Many Government or prime-contractor pyrotechnic managers do not have technical backgrounds to work on an equal basis with pyrotechnic manufacturers. This situation has led to the manufacturers educating the customer on the attributes of pyrotechnic applications, followed by the manufacturer being thrust into making a proposal without a reasonable understanding of system requirements. This approach results in a customer who is now largely dependent on the manufacturer for development of key pyrotechnic components without a clear definition on system interfacing. Also, the manufacturer should not be relied upon to investigate and resolve hardware failures with complete objectivity because of his vested interest. Finally, it is not reasonable to expect manufacturers to accomplish research and development to meet future requirements without considerable participation by the Government or prime contractor.

Test facilities.- The NASA and Air Force have very few test facilities that are designed for conducting pyrotechnic research, development and demonstration. Of the few facilities that exist, virtually all have to be reactivated and staffed on demand. This situation not only decreases the depth of understanding of personnel attempting to stay abreast and advance the state-of-the-art, but again forces reliance on the manufacturers.

Manpower.- Pyrotechnic personnel are generally transient, assigned or hired for a temporary effort on a specific program, and not encouraged to stay in the profession. Actually, many pyrotechnic staffs, including those in the NASA, are decreasing in the face of ever more demanding pyrotechnic applications. For example, McDonnell Aircraft Company, St. Louis, Missouri, a leader in pyrotechnic applications, such as crew escape systems in the Mercury, Gemini and the F-111 aircraft, in the past 3 years has experienced a reduction of senior staff from seven to three. NASA-JSC is the only Center that has recognized and reversed this trend.

Training.- No formal training exists that meets the needs for today's sophisticated pyrotechnic applications. There is no engineering curriculum devoted to pyrotechnics at any college or university. Very few safety courses are available to assure personnel safety in handling and using pyrotechnics, and to provide protection for systems in which pyrotechnics are applied. Personnel active in this field usually have received their education from the small handful of mentors described in the section on sources of information. There are few pyrotechnic personnel with the "hands-on" experience necessary to construct and apply the optimum approaches for design, development, qualification and lot acceptance testing. The greatest lack of experience is in testing to understand the mechanisms and relative importance of pyrotechnic system variables of pyrotechnic devices to prove functional margins.

Standards for requirements and hardware.- Most Centers develop their own specifications and hardware design philosophies, which can vary considerably. Also, managers in rushing to use "off-the-shelf" hardware to reduce costs, often discover a mismatch in form, fit or function, and then are forced into a redesign and "make-it-work" mode. Many potential users, such as university-sponsored experimenters, cannot afford to develop and qualify pyrotechnics for their particular system requirements. No low-cost, high-reliability components, other than the Government-furnished NASA Standard Initiator, are available. Hence, new products are continuously offered and the consequence is new problems or the reinvention of the old ones. There is no apparent motivation or general support for manufacturers to develop additional standardized components. However, difficulties have been encountered in the application of the NASA Standard Initiator. As designed, the output of the NASA Standard Initiator produces a dynamic (high-pressure/short-duration) output, which is suitable for its intended ignition function. However, problems have occurred in attempting to use its output to accomplish mechanical functions as a pressure generator.

Future requirements.- No shared approach has been established on recognizing pyrotechnic requirements or technology development needed for future missions. Unfortunately, technologists are trying to respond as the needs occur, without being able to develop a technology base or have the opportunity of participating in establishing advanced system definitions. This often leads to being "designed into a corner;" that is, forced to accomplish a function with pre-established limitations on input energy, weight, volume and output performance. Furthermore, since pyrotechnic systems are generally so unique (designed for specific applications) and costly, manufacturers cannot be expected to internally fund research and development to meet future requirements.

Funding.- There is no general research and development advocate nor fund source from either the NASA or the Air Force Space Division Headquarters dedicated to solving pyrotechnic problems and to meeting requirements for advanced aerospace pyrotechnic systems. All pyrotechnic funding is now earmarked by projects, whose limited schedules and funds often preclude or restrict new development. These restrictions force pyrotechnic managers to attempt to use supposedly "off-the-shelf" hardware, which often will not meet the current system requirements. This results in protracted, costly and inefficient design and development efforts.

CONCLUSIONS

In an effort to determine the causes of and preventing continuing failures in spacecraft systems using pyrotechnics, which are explosive and propellant-actuated mechanisms, excluding propulsion, a survey and analysis has been conducted on hardware failures that occurred in the final phases of system applications. That is, after design and in or following system qualification. The analysis included when and the causes for occurrence, the "state-of-the-art" that allowed failures and recommend improvements.

The total number of failures, including three deaths, reported in this survey was 84 for the 23-year period of the compilation with an average of 3.65 per year. The survey was an informal compilation, based on memory and limited documentation. No Center maintains a complete formal record of failures. Therefore, no technical problem data base has been established by this study. The failure rates per functional category were 32 in mechanisms, 30 in initiation, 14 in separation systems and 8 in electrical firing circuits. A total of 12, or over 14 percent, of the failures occurred in flight with 15 in qualification, 1 in manufacture following qualification, 33 in lot acceptance testing (LAT), 14 in systems tests, 5 in final assembly and 4 in service life evaluation tests. Clearly, some lot acceptance testing is adequate in discovering flaws in functional performance. However, some lot acceptance testing needs improvement, since more failures occurred after this testing than before.

For the source of failures, the shocking statistic is that 35 of 84 (42 percent) of the failures were caused by a lack of understanding; that is, the personnel working the problem at the time did not have the technology needed to understand and correct the failure. Unfortunately, 24 were mistakes, caused by poor designs and misapplication of hardware, which means that personnel did not apply the known technology. The next 22 failures have to be categorized as carelessness, through manufacturers' poor procedures and quality control. Program managers were at fault in three cases in not having established correct procedures and creating an incorrect specification.

The assessment as to the reasons why and how these failures occurred show the need for many improvements. Pyrotechnics should be recognized as an engineering technology, not considered a subsystem of other disciplines, or even worse "nuts and bolts" and magic. The lack of experienced personnel have discouraged program managers from early considerations of their use, even when important benefits can be achieved. Guidelines are needed for pyrotechnic system design, development, (which includes demonstration of functional margins), qualification and acceptance. Some past managers have actually implied that pyrotechnics cannot really be understood, and the best that can be done is to develop statistical verifications of success. That is, once a successful performance was achieved, reliability was based on repeated success. Statistical approaches are not a possible solution where cost is the key, particularly when entered into without knowing if the system is over- or marginally designed.

Inadequate communication and the lack of information have prevented the optimization of design approaches and failure analyses. Most Centers have worked pyrotechnic efforts independently. Few pyrotechnic publications exist, with no library or central source of information. Particularly lacking is a databank for failures. Without sharing, the opportunity for capitalizing on the varied experience of the handful of specialists in this country is limited.

There is an inadequate number of experienced pyrotechnic personnel and capable test facilities to assure successful system management. More experienced pyrotechnic personnel and test facilities are needed. Without sufficient manpower, training, and test facilities, program managers have had too great a reliance on manufacturers. Pyrotechnic personnel have no formal training opportunities, are generally transient, and are not encouraged to stay in the field. Consequently, too heavy a reliance on manufacturers has evolved in educating pyrotechnic managers, as well as proposing on pyrotechnic systems without an accurate definition of requirements. Furthermore, there is a need for personnel, working in active facilities to develop "hands-on" experience to become more knowledgeable customers, to manage system failure analyses, independent from the manufacturers' vested interests, and to conduct the necessary research and development to meet future requirements.

Too many specifications and too wide a variety of pyrotechnic devices exist, creating costly confusion in selection by users, as well as continually creating new problems or reinventing the old ones. Each Center has developed its own specifications and preferred hardware. Standardized specifications and hardware, extending the approach of providing Government-furnished equipment, would greatly facilitate consideration and use of pyrotechnic systems, as well as enhancing system reliability. However, to avoid the major pitfall of misapplying technology, clear definitions of system performance capabilities must be developed and documented.

No pyrotechnic technology planning exists on an agency-wide basis. There is a need to develop overall NASA Headquarters-sponsored planning to manage this discipline. Headquarters advocates are needed for administrative and funding support to influence all administrative levels to recognize the activities necessary to elevate pyrotechnics to a technology and incorporate this technology into an active role in management structures, create a problem reporting and communication system, and provide the necessary funding, independent from major program offices, to accomplish in-house applicational studies, failure analyses and research and development.

RECOMMENDATIONS

The following recommendations are offered for meeting the pyrotechnic technology needs described in the above conclusions:

1. Continue inter-Center coordination through the NASA/DOD Aerospace Pyrotechnic Systems Steering Committee and symposia activities to:

   a. Promote technology exchange

   b. Assist in problem solving and failure resolution

   c. Support design reviews

   d. Conduct independent technical assessments of systems.

2. Provide guidelines, handbooks and specifications for design, development, qualification, lot acceptance, safety, reliability and quality assurance

3. Encourage recruitment and retention of pyrotechnic personnel

4. Provide safety and engineering training, including "hands-on" experience

5. Compile experience through a NASA-wide pyrotechnic problem reporting system to maintain a technology base.

6. Expand the concept of Government-furnished equipment with clearly defined functional capabilities.

7. Recommend and implement pyrotechnic planning to improve personnel experience and provide for needed technology and development.

REFERENCES

1. Halpert, Gerald: Flight Battery Problems, Their Causes and Impact, A Survey for NASA Headquarters. JPL D-3207, May 1986.

2. Bement, Laurence J. and Schimmel, Morry L.: Investigation of Super*Zip Separation Joint. NASA TM-4031, May 1988.

3. DOD-E-83578A, "Explosive Ordnance for Space Vehicles". October 15, 1987.

TABLE I

NASA/DOD AEROSPACE PYROTECHNIC SYSTEMS

STEERING COMMITTEE MEMBERS

NAME	AFFILIATION
Norman R. Schulze, Chairman	NASA Headquarters
William J. Fitzgerald (Air Force)	Aerospace Corporation
Richard G. Plihal	NASA Goddard
Michael Zydowicz	Jet Propulsion Lab
Thomas Graves	NASA Johnson
Garland Thomas	NASA Kennedy
Laurence J. Bement	NASA Langley
Thomas Seeholzer	NASA Lewis
Joe B. Davis	NASA Marshall
Gerald Laib	Naval Surface Warfare Center

TABLE II

FAILURE SOURCE CATEGORIES AND DEFINITIONS

1. Incorrect Specification - An unnecessary or erroneous requirement.

2. Bad System Test Procedures - System test procedures inadequate or erroneous.

3. Manufacturer's Poor Quality Control - All quality control in place, but not followed.

4. Manufacturer's Bad Procedures - The quality control procedures or manufacturing methods inadequate.

5. Bad Design - Personnel did not apply known technology.

6. Lack of Understanding - Personnel did not have the needed technology.

7. Misapplication of Hardware - Use of previously qualified device in an inappropriate application.

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1987	Classified	NSI failed to fire during separation nut test (vibration-induced separation of pyrotechnic mix from bridgewire)	Loss of lot and potential loss of redundancy and mission	Lack of understanding	Rejected lot, qualified new lot
1986	PAM	Bridgewire resistance LAT failures following electrostatic testing and shipment	Loss of lot	Lack of understanding	Rejected lot
1986	Universal Application	NASA Standard Initiator (NSI) failed to function in Lot Acceptance Testing (LAT) at -260° F	Indication of basic weakness of NSI, as well as potential loss of cold-temperature missions in STS or wide variety of spacecraft missions	Lack of understanding	Still in work
1986	Centaur	Detonator functioned in electrostatic discharge LAT (incapable of shunting energy away from explosive)	Potential premature initiation in handling, installation, and in ground test	Lack of understanding	Changed procedures, reduced requirement

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1986	HALOE	Pinpuller for telescope cover failed to function at high-current input in systems development (foil bridgewire broke too soon)	Potential loss of redundancy and loss of mission	Lack of understanding	Redesigned, requalified
1985	Centaur	Detonator for staging failed to function in LAT (bridgewire-to-propellant separation)	Potential loss of redundancy and loss of mission	Lack of understanding and manufacturer's bad procedures	Redesigned, new loading procedures and requalified
1984	Sidewinder Missile	Initiator failing LAT due to 3% of lot exhibiting increased resistance to open circuits (time dependent corrosion of bridgewire)	Potential loss of redundancy and loss of mission	Manufacturer's poor quality control	Could not duplicate failure. Cleaned up plant, enhanced control
1984	Universal Application	NASA Standard Initiator (NSI) failed in LAT (required too much time to function)	Potential loss of redundancy and loss of mission for wide variety of spacecraft applications	Lack of understanding	Rejected lot, revised manufacturing procedures

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1982	Shuttle	SRB explosive transfer manifold side bushing failed in LAT(bushing ejected)	Potential damage to Shuttle from fragment impact	Manufacturer's poor quality control	Rejected lot
1982	Classified	Rocket motor initiator bridgewires opened (overtorquing during installation)	Potential loss of redundancy, loss of mission	Lack of understanding	Reduced installation torque, redesigned, requalified
X1982	Classified	Initiators failed to fire at 7-ampere flight level; developed at 3.5 amperes	Loss of mission	Lack of understanding	Redesigned, requalified X
1981	Delta	Detonator for rocket assist failed in LAT (extraneous wire across bridgewires	Potential loss of redundancy, loss of mission	Manufacturer's poor quality control	Increased quality control
1981	Shuttle	SRB nozzle severance charge failed LAT (large particle explosive)	Potential increased damage to SRB case at water impact	Bad design	Redesigned, restricted use of recycled explosive, requalified

XXXXXXXX FLIGHT FAILURE

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1981	Delta	Explosive transfer assembly failed to function in LAT (overheated explosive in welding assembly)	Potential loss of redundancy, loss of mission	Manufacturer's poor quality control	Rejected lot, increased quality control
1979	Classified	Initiator failed LAT -65° F firing (improper firing current)	Loss of lot, potential loss of redundancy and mission	Lack of understanding	Manufactured new lot
1978	Shuttle	Crew escape explosive transfer line failed to propagate in LAT (explosive cord overcompressed in swaging assembly)	Potential loss of redundancy, loss of escape capability	Bad manufacturer's procedure	Rejected lot, modified tooling and manufacturing procedures
1978	Delta	Cutter failed to function in ground test (misapplication of current below all-fire level before applying firing signal	Delay of test, loss of hardware	Bad system test procedures	Improved quality control: procedures and equipment calibration
1977	Delta	Explosive bolt failed to function in LAT (misplaced component in initiator)	Potential loss of redundancy, loss of mission	Manufacturer's bad procedures	Rejected lot, increased quality control

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1977	Delta	Detonator (one of lot) functioned in electrostatic LAT	Potential personnel hazard, premature function in prelaunch	Manufacturer's poor quality control	Accepted lot
1977	Delta	Explosive transfer lines for rocket assist ignition failed to propagate in LAT (tip seal intruded into gap and blocked output of donor explosives)	Delay of flight. Potential loss of redundancy and loss of mission	Bad design	Redesigned (shortened tip seal)
1976	Delta	Rocket assist safe/arm failed to propagate in LAT (improperly retained transfer charge)	Delay of flight. Potential loss of redundancy and loss of mission	Bad design	Redesigned, requalified
1974	Classified	Valve cartridge failed LAT (extremely long inconsistent function times)	Schedule delay	Lack of understanding	Changed vendor, used bridgewire instead of thin film bridge
1974	Classified	Initiator failed to fire in functional test (slurry bridgewire mix flaking off in two-year time frame)	Potential loss of redundancy and mission	Lack of understanding	Redesigned, requalified

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1972	Viking	Standard initiator failed to function under cold-temperature LAT	Potential loss of redundancy and loss of mission	Lack of understanding	Enhanced quality control
1971	Classified	Reefing cutter failed during system test (manufacturer's change in delay mix which resulted in inability to ignite output charge)	Potential loss of redundancy and mission	Manufacturer's poor quality control	Redesigned, requalified
1969	Classified	Cartridges failed to fire in service life evaluation (loss of seal)	Potential loss of redundancy and mission	Bad design	Redesigned, requalified
1968	Universal Application	Apollo standard initiator functioned in electrostatic LAT (epoxy in spark gap)	Potential hazard to personnel, premature initiation	Manufacturer's bad procedures	Modified manufacturer's procedures and quality control
1967	Apollo	End detonating cartridge for interstage guillotine failed to function in LAT (alcohol intrusion into explosive)	Potential loss of redundancy, loss of mission	Manufacturer's bad procedures	Modified manufacturer's procedures and quality control

TABLE III

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

INITIATION (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
X1966	Atlas	Redundant detonators failed to initiate vehicle destruct (contaminated explosive degradation)	Loss of mission	Manufacturer's bad procedures	Scrapped lot; enhanced procedures and quality control
1964	Delta	Electrostatic discharge ignition of squib in 500-pound solid rocket motor in vertical stand	3 people killed, 8 injured. Delay of flight	Lack of understanding	Redesigned squib and igniter

XXXXXXXX FLIGHT FAILURE

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1987	FLTSATCOM	Initiator output performance degrading in service life program	Potential loss of lot	Lack of understanding	Increased frequency of surveillance testing
1987	Magellan	Pin puller failed to stroke against flight side load (NSI output restricted, causing reduced output and housing deformation against working piston)	Potential loss of mission	Bad design, misapplication of hardware	Replaced, requalified
1986	TITAN 34D	Fairing detonator failed LAT output test (Charge displaced in temperature cycling)	Potential loss of redundancy and mission	Lack of understanding	Redesigned, requalified
1986	ASAT	Bolt cutter failed LAT (improper compression margin test requirement)	Unnecessary failure analysis, additional testing ($300K)	Incorrect specification	Correct specification
1986	Magellan Orbiter	Pinpuller failed to function in LAT (NSI produced insufficient pressure caused by coatings of pressurized volume)	Potential loss of redundancy, loss of mission	Misapplication of hardware, lack of understanding	Changed manufacturer and design

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1985	Magellan	Release nut failed in flight qualification at 50% propellant load	Potential loss of redundancy, loss of mission	Lack of understanding	Redesigned
1985	Shuttle	Shuttle Orbiter/ET separation bolt failed to meet LAT load requirements (crack in shank)	Potential premature function, loss of mission	Manufacturer's bad procedures	Improved heat treatment and quality control
1984	INTELSAT V	Separation nut delivered with an internal gas port missing	Potential loss of mission	Manufacturer's poor quality control	Ensure compliance with procedures
1984	Shuttle	Shuttle Orbiter/ET separation bolt failed to produce clean separation plane in qualification (internal piston extended beyond separation plane)	Potential interference in separation, loss of mission	Bad design	Redesigned, requalified
X1984	Shuttle	Nosegear extension thruster failed (actuation piston parted)	Potential loss of Orbiter	Bad design	Redesigned and requalified X

XXXXXXXX FLIGHT FAILURE

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1983	Galileo	Bellows actuator for lens cover failed in qualification (housing ruptured, venting propellant residue)	Potential loss of redundancy, contamination of experiment, loss of photo-optical data	Manufacturer's poor quality control	Improved manufacturer's quality control
1983	Galileo Ulysses	Release nut failed to function in qualification (NSI delivers insufficient energy)	Potential loss of mission	Misapplication of hardware, lack of understanding	Redesigned (increased propellant load)
1983	Ground Test Fixture	Explosive bolts experienced tensile failures during load transfer carriage drop testing (hydrogen embrittlement)	Loss of experiment	Manufacturer's bad procedures	Define material and processing procedures with additional demonstration
1982	Delta	Cartridge exceeded maximum allowable output in LAT	Potential damage to structure	Bad design	Redesigned (decreased propellant load); repeated LAT
1980	IUS	Redundant detonator failed to function after being subjected to shock generated by first detonator	Potential loss of redundancy and mission	Lack of understanding	Redesigned, requalified

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1980	DSCS III	Separation nut released when subjected to qualification mechanical shock test. Nut modified to use only NSI	Potential premature release and loss of mission	Misapplication of hardware, lack of understanding	Redesigned
1980	Shuttle	SRB nose cap thruster cartridge produced too low output in LAT	Potential failure to jettison nose cap, loss of spent SRB	Manufacturer's poor quality control	Rejected lot
1979	Classified	Initiators failed LAT output performance (low pressure and long ignition delay. Material incompatibility)	Loss of lot, potential loss of redundancy and mission	Lack of understanding	Redesigned, requalified
1979	Classified	Parachute drogue mortar tube fractured (high pressures created by NSI fracturing propellant)	Potential contamination or damage to spacecraft, reduction in performance, loss of mission	Lack of understanding	Redesigned interface

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1979	Classified	Pin puller body ruptured during system test (inadequate containment margin and variation in metal grain orientation)	Potential contamination of spacecraft, reduction in performance	Lack of understanding	Redesigned, requalified
1978	Centaur	Atlas Centaur nose fairing explosive bolt exhibiting wide range of strengths in qualification (manufacturing variations in hardness)	Potential premature or failure to function, loss of mission	Manufacturer's bad procedures	Modify procedures to machine grooves, based on material hardness
1976	TREP	Through-bulkhead initiators failed to function in LAT high-temperature tests (contaminated explosive)	Loss of lot, potential loss of redundancy, loss of mission	Manufacturer's bad procedures	Enhanced procedures and quality control
1976	SKYNET	Explosive transfer line connector blown off a redundant through-bulkhead initiator in ignition test (rearward detonation)	Potential spacecraft damage and contamination	Lack of understanding	Redesign

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1976	RSRA	Firing pin assemblies corroded and locked in qualification	Potential loss of redundancy, loss of aircraft and crew	Bad design	Redesigned, requalified
X1975 X X	Nike/Apache	Payload door bellows failed in flight to release door	Loss of mission	Bad design	Redesigned, requalified X X X
X1974 X X	Nike/Apache	Payload door bellows failed in flight to release door	Loss of mission	Bad design	Redesigned, requalified X X X
1973	Classified	Pin puller failed during system test (cartridge closure blocking port)	Potential loss of redundancy and mission	Lack of understanding	Redesigned, requalified
1972	Centaur	Atlas Centaur nose fairing explosive bolt failed in qualification (secondary piston parted after bolt actuation)	Potential damage to spacecraft due to debris	Bad design	Redesigned, requalified

XXXXXXXX FLIGHT FAILURE

TABLE IV

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

MECHANISMS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
X1970	Centaur	Atlas Centaur nose fairing explosive nut failed to separate in flight (nut segments imbedded in washer)	Loss of mission	Bad design	Redesigned and incorporated explosive bolts to provide redundancy
1969	Small Launch Vehicle	Explosive bolt functioned during vibration testing in qualification	Potential personnel safety hazard, premature function, loss of mission	Bad design	Redesigned, requalified
1968	Classified	Door release assembly failed to function (nonsimultaneity of four-point release system)	Potential loss of mission	Lack of understanding	Redesigned, requalified
1966	Classified	Piston actuator for high-temperature electrical switch failed to function (inadequate capability)	Potential loss of redundancy and mission	Lack of understanding	Redesigned, requalified

XXXXXXXX FLIGHT FAILURE

TABLE V

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

SPACECRAFT SEPARATION JOINTS AND LINEAR EXPLOSIVES

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1984 1983	Shuttle/ Centaur	Separation joint failed to separate in cold-temperature development (plates to be fractured too thick and too soft)	Potential delay of mission, loss of mission, loss of Shuttle	Lack of understanding	Revised quality control on plates, increased explosive load
1984	Centaur	Severance charge forward seal failed to initiate in LAT (improper assembly)	Potential loss of mission	Bad design and procedures	Improved quality control and tooling
1984	Galileo	Separation joint failed margin tests with reduced explosive load in qualification	Potential loss of mission	Lack of understanding	Redesigned, increased explosive load
X1984 X X X X X	Centaur	Atlas Centaur AC62 failed in flight at time of staging (separation charge contributed to existing oxygen leak)	Loss of mission	Manufacturer's bad procedures in tank assembly	Improved manufacturer's quality control X X X X X X

XXXXXXXX FLIGHT FAILURE

TABLE V

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

SPACECRAFT SEPARATION JOINTS AND LINEAR EXPLOSIVES (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1983	Centaur	Severance charge forward seal failed to initiate in LAT (solvent contamination)	Potential loss of mission	Manufacturer's bad procedures	Improved quality control
1982	Shuttle	External tank destruct charge failed to achieve penetration in LAT	Potential inability to destruct tank	Manufacturer's bad procedures	Rejected lot
X1979	Trident	Flight failure of Trident missile separtion joint	Loss of missions	Lack of understanding	Redesigned, requalified
X1978	Trident	Flight failure of Trident missile separtion joint	Loss of missions	Lack of understanding	Redesigned, requalified
1978	Centaur	Severance charge forward seal failed LAT (sheath porosity)	Potential loss of mission	Manufacturer's bad procedures	Improved quality control

XXXXXXXX FLIGHT FAILURE

TABLE V

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

SPACECRAFT SEPARATION JOINTS AND LINEAR EXPLOSIVES (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1972	Apollo	Docking ring failed to separate in Skylab ground test	Delayed flight; potential loss of redundant system	Lack of understanding, manufacturer's bad procedures	Improved quality control
1969	Apollo	Apollo-Service Module/Lunar Module adaptor severance charge failed to function in LAT (RTV solvent attacked cord)	Potential loss of redundancy, loss of mission	Bad design	Redesigned, requalified
X1968	ATHENA	Linear shaped charge failed to sever nose cone (damage caused by first detonator to fire)	Loss of mission	Lack of understanding	Redesigned, requalified X
1968	ATHENA	Linear shaped charge failed to initiate in service life evaluation	Discarded unacceptable material	Lack of understanding	Used verified material

XXXXXXXX FLIGHT FAILURE

TABLE VI

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

FIRING CIRCUITS

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1987	Sounding Rockets	Lightning strike at launch site ignited 3 of 4 rockets readied for launch (Electromagnetic induced energy in partially shielded and grounded firing leads)	Loss of mission	Bad design	Complete firing circuit shielding, enhance lightning protection
1987	Shuttle	Pyrotechnic Initiator Controller (PIC) circuit board resistors failing (Outer seal thermally cracking, allowing solvents to attack internal element)	Units being rebuilt.	Bad design	Replace all resistors
1983	Aircraft Crash Test	Aircraft crash test program discovered stray voltage in facility firing circuits in flight checkout (poor grounding and corrosion of cables/connectors)	Delay of experiment and potential loss of life and loss of experiment	Bad system test procedures	Rebuilt checkout/firing cables and consoles

TABLE VI

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

FIRING CIRCUITS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
X1982	Shuttle	SRB decelerator parachute released prematurely in flight at Frustrum separation (pyrotechnic shock activation of water impact sensor)	Loss of spent SRB's	Lack of understanding	Redesigned, requalified
X1981	Shuttle	SRB nozzle failed to sever in flight (damaged electrical cable)	Increased damage to SRB case at water impact	Bad design	Redesigned
1978	TITAN III	Destruct safe/arm failed to arm on launch pad (incorrect interface tolerances mechanically prevented actuation)	Delay of flight	Bad design	Redesign

XXXXXXXX FLIGHT FAILURE

TABLE VI

NASA/AIR FORCE AEROSPACE PYROTECHNIC FAILURES

FIRING CIRCUITS (CONTINUED)

DATE	PROJECT	FAILURE	IMPACT	SOURCE OF FAILURE	RESOLUTION
1972	Centaur	Shroud separation joint fired primary and secondary charges simultaneously in qualification and ruptured containment (connectors on firing circuits swapped)	Damaged test hardware, potential damage to spacecraft and flight vehicle	Bad design	Redesigned, different connectors
1970	ATHENA	Lanyard-actuated safe and arm failed qualification (inability of device to function under launch acceleration)	Modified launch procedure to arm on pad	Lack of understanding	Unresolved failure

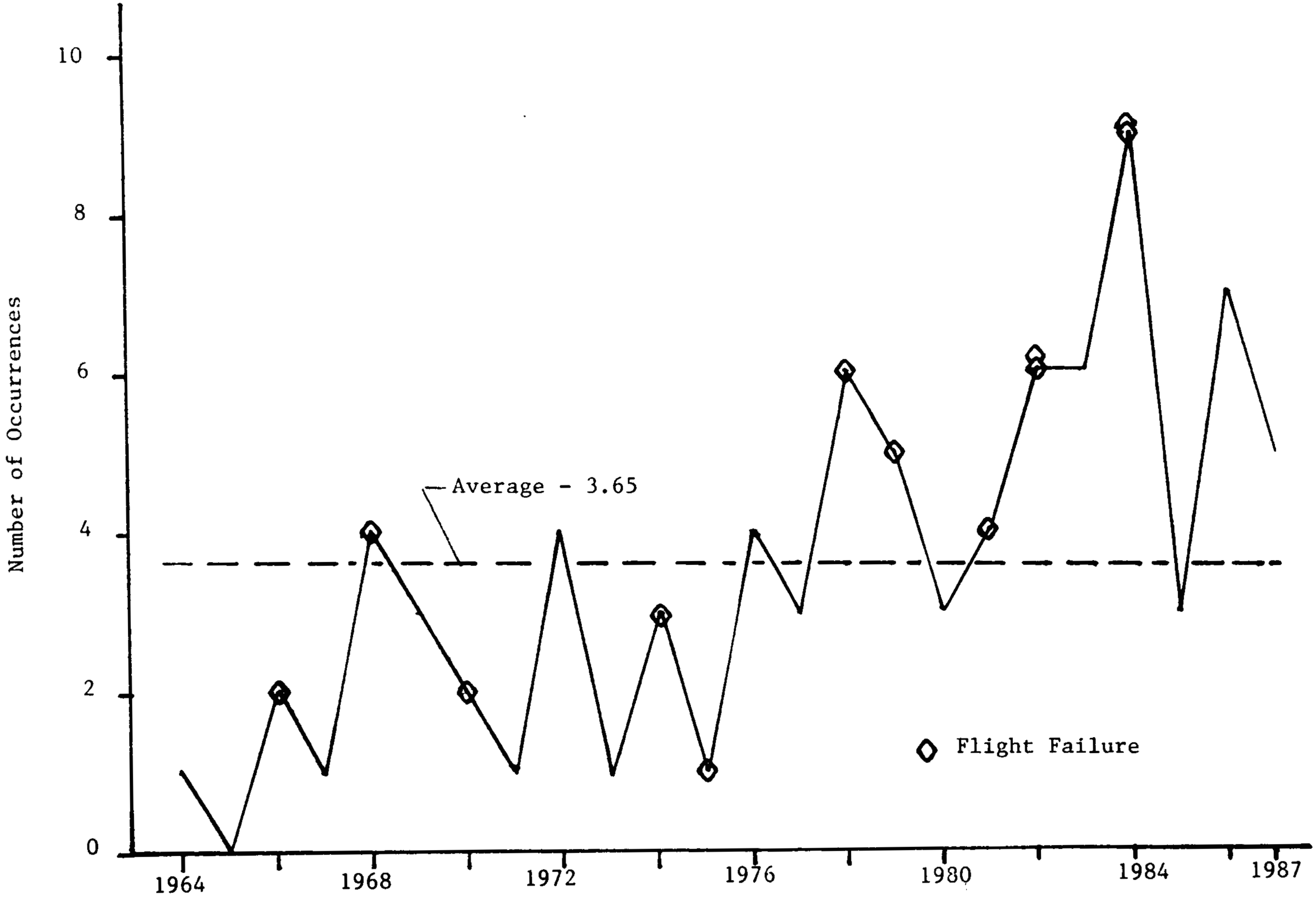

Figure 1.- Frequency of pyrotechnic failures .

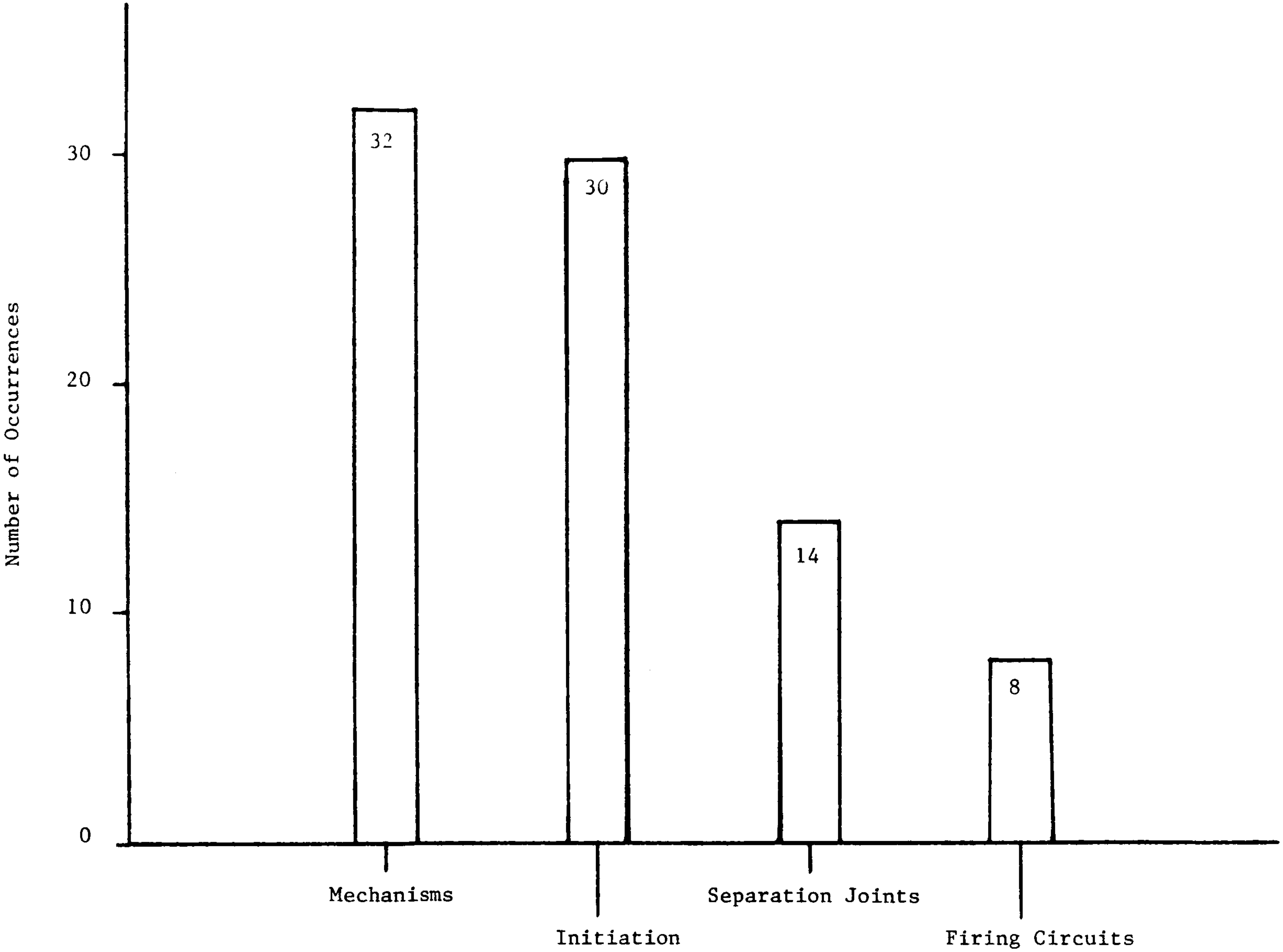

Figure 2.- Frequency of pyrotechnic failures in functional categories.

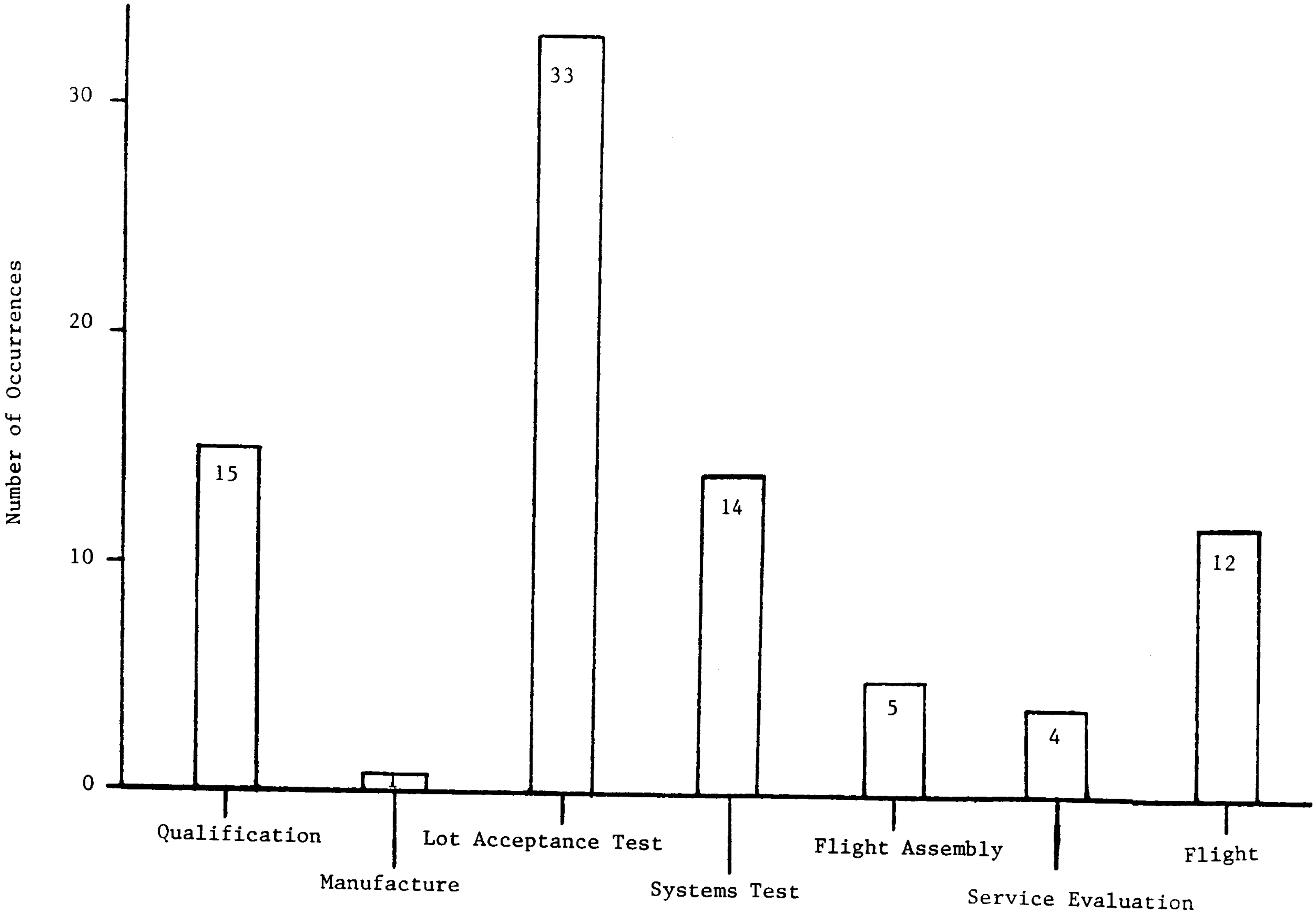

Figure 3.- Frequency of pyrotechnic failures occurring in device life cycle.

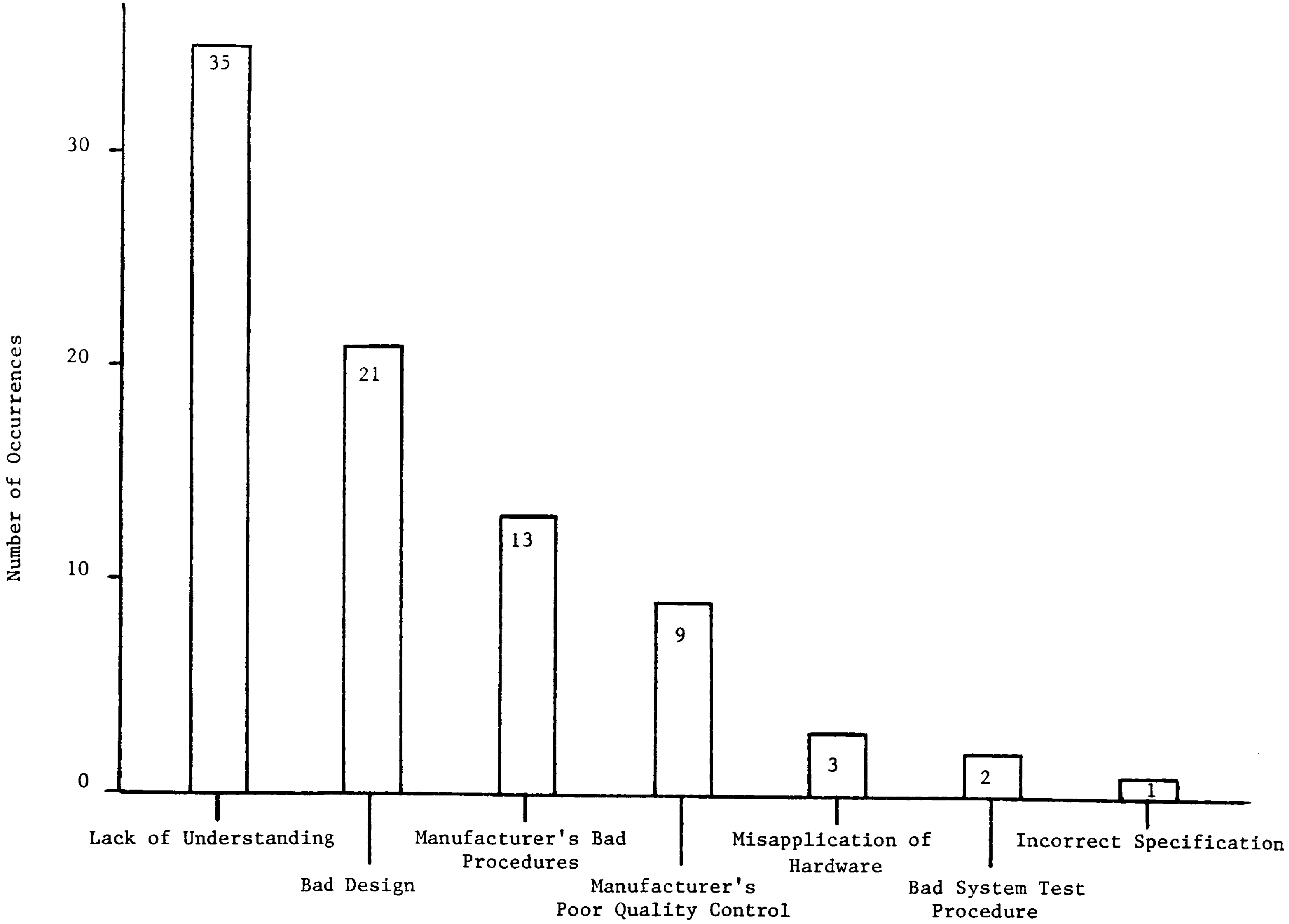

Figure 4.- Frequency of pyrotechnic failure occurring by cause.

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16. Abstract

Although pyrotechnics have successfully accomplished many critical mechanical spacecraft functions, such as ignition, severance, jettison and valving (excluding propulsion) failures continue to occur. This paper provides a listing of 84 failures of pyrotechnic hardware with completed design over a 23-year period, compiled informally by experts from every NASA Center, as well as the Air Force Space Division and the Naval Surface Warfare Center. Analyses are presented as to when and where these failures occurred, their technical source or cause, followed by the reasons why and how these kinds of failures continue to occur. The major contributor is a fundamental lack of understanding of the functional mechanisms of pyrotechnic devices and systems, followed by not recognizing pyrotechnics as an engineering technology, insufficient manpower with "hands-on" experience, too few test facilities, and inadequate guidelines and specifications for design, development, qualification and acceptance. Recommendations are made on both a managerial and technical basis to prevent failures, increase reliability, improve existing and future designs and develop the technology to meet future requirements.

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