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PYROSHOCK TEST CRITERIA

MEASUREMENT SYSTEM IDENTIFICATION: METRIC/SI (ENGLISH)

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DOCUMENT HISTORY LOG

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FOREWORD

This Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This Standard is approved for use by NASA Headquarters and all NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Standard establishes a methodology for developing pyroshock test criteria for NASA spacecraft, payload, and launch vehicle hardware for development, qualification, flight acceptance, and/or protoflight test verifications. The state-of-the-art for pyroshock prediction, design and test verification has not yet reached the maturity of other environmental disciplines due to the complex, high-frequency nature of pyroshocks. However, recent advances in the measurement and analysis of pyroshocks have led to a better understanding of this environment.

Requests for information, corrections, or additions to this Standard should be submitted via “Feedback” in the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov.

Original Signed By:	***12/20/2011***
Michael G. Ryschkewitsch NASA Chief Engineer	Approval Date

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PYROSHOCK TEST CRITERIA

1. SCOPE

1.1 Purpose

The purpose of this Standard is to provide a consistent methodology for developing pyroshock test criteria for NASA spacecraft, payload, and launch vehicle hardware during the development, qualification (Qual), flight acceptance (FA), and/or protoflight (PF) test phases of the verification process. Various aspects of pyroshock testing are discussed herein, including test environments, methods and facilities, test margins and number of exposures, control tolerances (when applicable), data acquisition and analysis, test tailoring, dynamic analysis, and prediction techniques for pyroshock environments.

The most accurate simulation of the flight pyrotechnic environment is obtained for potentially susceptible hardware by testing with flight pyrotechnic devices on actual or closely simulated flight structure. However, high-fidelity flight structure is not usually available early in a program, and this approach does not provide magnitude qualification margin over flight. The alternative approach described in this Standard is to perform qualification or protoflight pyroshock simulation tests on potentially susceptible flight or flight-like hardware assemblies as early as possible, then to activate actual pyrotechnic devices on the flight system to improve pyroshock environment predictions and as a final verification. The advantages of this approach are that it may reveal potential hardware deficiencies early in the development program, and it allows the application of a qualification/protoflight margin to assembly-level pyroshock tests. The disadvantages include the potential for incorrect estimates of the pyroshock environment due to limitations of measurement methods and analysis techniques available today and the difficulty in accurately simulating a specified pyroshock environment at the assembly level. Regardless, testing on actual or closely similar flight structures is essential for final system verification.

1.2 Applicability

This Standard is applicable to the development of pyroshock test criteria for NASA spacecraft, payload, and launch vehicle hardware during the development, qualification, flight acceptance, and/or protoflight test phases of the verification process. Verification programs that meet or exceed the endorsed requirements for pyroshock testing set forth in this document shall be considered compliant with this Standard.

Shock testing requirements for hardware utilized in Range Safety Systems, and the methodology for tailoring those requirements for a specific program, are contained in Air Force Space Command Manual 91-710 (AFSPCMAN91-710). The Range has specific requirements for margins, minimum test levels, number of shock applications during testing, test tolerances, and testing unique to shock isolators.

This Standard is approved for use by NASA Headquarters and NASA Centers, including

Component Facilities and Technical and Service Support Centers, and may be cited in contract, program, and other Agency documents as a technical requirement. This Standard may also apply to the Jet Propulsion Laboratory or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

Requirements are numbered and indicated by the word “shall.” Explanatory or guidance text is indicated in italics beginning in section 4.

1.3 Tailoring

Tailoring of this Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the Technical Authority.

1.4 Background

1.4.1 Pyrotechnic Applications

Current launch vehicle, payload, and spacecraft designs often utilize numerous pyrotechnic devices over the course of their missions. These devices are generally used to separate structural subsystems (e.g., payloads from launch vehicles), deploy appendages (e.g., solar panels), and/or activate on-board operational subsystems (e.g., propellant valves).

1.4.2 Pyroshock Characteristics

The initial pyroshock peak acceleration may be as high as 200,000 g with high frequency content as high as 1 MHz; these derived characteristic values are highly dependent on the method of measurement and recording as well as the subsequent digital data analysis. The pyroshock acceleration time history has a short duration (less than 20 ms) and is also largely dependent on the source type and size or strength, intervening structural path characteristics (including structural type and configuration, joints, fasteners and other discontinuities) and distance from the source to the response point of interest. Because of the high frequency content, many hardware elements and small components are susceptible to pyroshock failure while resistant to a variety of lower frequency environments, including random vibration. High frequencies may make analytical methods and computational procedures inapplicable for system verification under pyroshock loading.

a. Pyroshock verification shall be accomplished by Qual and FA or PF testing.

b. Successful pyroshock testing shall be considered essential to mission success.

1.4.3 Potential Hardware Effects

Many flight hardware failures have been attributed to pyroshock exposure, some resulting in catastrophic mission loss (Moening, C.J. (1984)). Specific examples of pyroshock failures include cracks and fractures in crystals, ceramics, epoxies, glass envelopes, solder joints and wire leads, seal failure, migration of contaminating particles, relay and switch chatter and transfer of state, and deformation of very small lightweight structural elements, such as microelectronics. On the other hand, deformation or failure of major structural elements is rare except in those regions close to the source where structural failure is intended.

1.5 Summary of Pyroshock Level of Assembly and Environmental Categories

The pyroshock environment for most assemblies is externally-induced, thus assembly level pyroshock qualification is usually performed using a simulated pyroshock source that includes a 3 dB margin over the maximum expected flight environment. (See section 3.2.6 for a detailed discussion of externally-induced and self-induced shocks.) For the purposes of selecting the appropriate simulated shock test method, this Standard divides the pyroshock environment into the following three categories, depending on the shock severity and frequency range, as follows: First, near-field; second, mid-field; and third, far-field. Detailed definitions are provided in section 3.2.3. The intent of this categorization is to assist hardware and test personnel in the selection of appropriate test techniques and facilities. For the near-field, generally only pyrotechnic devices should be used. For the mid-field, either mechanical impact or pyrotechnic devices should be used. For the far-field, electrodynamic shakers, impact or pyrotechnic devices may be used.

The pyroshock environment for most spacecraft systems, many large subsystems, and occasionally some assemblies are self-induced. Self-induced shocks are simulated using the actual pyro device and flight or flight-like intervening structure. This Standard requires 3 dB margin (or 1.4 x maximum expected flight environment (MEFE)) for qualification for pyroshock environments; but if the actual hardware and pyro devices are used, then it will not be possible to achieve the 3 dB margin (or 1.4 x MEFE). Consequently, multiple firings of actual pyro devices and instrumentation of potentially shock sensitive components contained in the test article are required to validate lower level pyroshock test specifications.

1.6 Summary of Pyroshock Test Criteria

A summary of the mandatory requirements is given in this section. Mandatory pyroshock test margins are summarized in table 1. Specific pyroshock test requirements are selected based on the following:

a. The flight or service pyroshock environment as defined in section 3.2.3.

b. The environment test categories described in section 3.2.5.

c. The level of assembly defined in section 3.2.6.

d. The MEFE as specified in section 4.2.

e. Test margins as discussed in section 4.3.

f. Test specifications described in section 4.4.

g. The test method and facility as outlined in section 4.5.

1.6.1 If there is a question about the hardware susceptibility to pyroshock, then pyroshock testing shall be performed. (See section 4.1.1.)

Table 1—Summary of Pyroshock Test Margins

Pyroshock Type	Qualification	Protoflight	Flight Acceptance
Self-Induced/Actual Device	2 Actuations	2 Actuations	1 Actuation
Externally-Induced/Simulated	MEFE + 3 dB 2x Each Axis	MEFE + 3 dB 1x Each Axis	MEFE 1x Each Axis

1.6.2 Pyroshock verification shall be accomplished by Qual and FA or PF testing.

1.6.2.1 Successful pyroshock testing shall be considered essential to mission success. (See section 4.1.2.1)

1.6.3 Pyrotechnic test criteria shall be based upon the MEFE or service environment. (See section 4.2.1)

1.6.4 When statistical analysis is selected, the MEFE shall be based on P95/50 statistics of shock response spectrum (SRS) data. (See section 4.2.2.)

1.6.5 Pyroshock Qual testing for externally-induced pyroshock environments shall be performed with a magnitude margin added to the MEFE to account for failure due to hardware variability.

1.6.5.1 A minimum Qual margin of 3 dB (or 1.4 x MEFE) shall be added to the MEFE uniformly across the spectrum for pyroshock Qual testing. (See section 4.3.1.1)

1.6.6 A minimum of two shock applications per axis for externally-induced shock environments shall be applied for pyroshock Qual testing. (See section 4.3.2.)

1.6.7 When performed, FA testing for externally-induced shock environments shall be conducted at MEFE conditions with one shock application per axis. (See section 4.3.3.)

1.6.8 PF testing for externally-induced shock environments shall be performed at Qual magnitude (or 1.4 x MEFE) with one application per axis. (See section 4.3.4.)

1.6.9 For Qual and PF testing for self-induced shocks, a minimum of two firings of the flight pyrotechnic devices shall be performed for those devices that generate the dominant pyroshock environment for potentially sensitive equipment. (See section 4.3.5.)

1.6.10 For devices that do not generate the dominant pyroshock environment for potentially sensitive equipment, the pyrotechnic devices shall be fired once to verify that they do not generate a more severe shock condition for any potentially susceptible hardware. (See section 4.3.6.)

1.6.11 When FA testing is performed for self-induced shocks, one firing of the flight pyrotechnic devices shall be performed for those devices that generate the dominant pyroshock environment for potentially sensitive equipment. (See section 4.3.7.)

1.6.12 System-level pyrotechnic device test firings shall be adequately instrumented to verify assembly level requirements. (See section 4.4.1.)

1.6.13 Pyroshock tests to simulate externally-induced environments shall be specified using maximax SRS with a constant quality factor of Q=10, based on the MEFE described in section 4.2 and a margin described in section 4.3, and over a natural frequency range consistent with the appropriate pyroshock environment (i.e., near, mid, or far-field) as defined in section 4.4. (See section 4.4.2.)

1.6.14 The pyroshock test to simulate externally-induced environments shall achieve the required SRS within the tolerances specified in section 4.8 for three-orthogonal axes. (See section 4.4.3.)

1.6.15 The pyroshock test waveform or time history shall have similar oscillatory characteristics to that of the predicted flight event with a total duration similar to that of the predicted flight event and no longer than 20 ms. (See section 4.4.4.)

1.6.16 If pyroshock-sensitive hardware is located so that it is exposed to the near-field environment, near-field testing shall be required. (See section 4.4.5.)

1.6.17 Before analog-to-digital conversion (ADC), anti-aliasing filters shall be applied to the analog signals. (See section 4.6.1.)

1.6.18 The tolerances most commonly used in current aerospace practice are specified for the maximax SRS and shall be used:

Natural Frequency	Tolerance
$f_n \leq 3$ kHz	±6 dB

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$f_n > 3$ kHz	+9/-6 dB

1.6.18.1 The SRS shall be calculated with a resolution of at least one-sixth (1/6) octave band for the natural frequency range of the test specification.

1.6.18.2 At least 50 percent of the SRS magnitudes shall exceed the nominal test specification.

1.6.18.3 The acceleration time history used to create the SRS for the laboratory pyroshock simulation shall be preserved for comparison to the flight acceleration time history. (See section 4.8.1.)

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this Standard as cited in the text.

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov or may be obtained directly from Standards Developing Organizations or other document distributors.

2.2 Government Documents

NASA

NASA-HDBK-7005	Dynamic Environmental Criteria
NASA-STD-7002A	Payload Test Requirements
NASA-STD-8719.12	Safety Standard for Explosives, Propellants, and Pyrotechnics

U.S. AIR FORCE

AFSPCMAN91-710	Air Force Space Command Manual 91-710

2.3 Non-Government Documents

None.

2.4 Order of Precedence

This Standard establishes requirements for uniform usage of test factors in the pyroshock verification process for NASA spacecraft, payload, and launch vehicle hardware but does not supersede nor waive established Agency requirements found in other documentation.

2.4.1 Conflicts between this Standard and other requirements documents shall be resolved by the responsible Technical Authority. In general, the most stringent of the documents should be used.

2.4.2 Safety considerations that are covered thoroughly in other documents are not addressed in this Standard; but if a conflict arises, safety shall always take precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. ACRONYMS, SYMBOLS, AND DEFINITIONS

3.1 Acronyms and Abbreviations

%	percent
β	fractional portion
γ	confidence coefficient
δ	difference
ζ	fraction of critical damping or viscous damping ratio
∞	infinity
ADC	analog-to-digital converter
AIAA	American Institute of Aeronautics and Astronautics
D	distance
dB	decibels
E	total energy
f	frequency
FA	flight acceptance
FEM	finite element method
ft	feet
g	acceleration of gravity, usually 9.807 m/s^2 = 386.1 in/s^2
Hz	Hertz or cycles per second
i	sample number
in	inches
ISO	International Organization for Standardization

k	kilo or 10^3
kHz	kilohertz
$k_{n,\beta,\gamma}$	normal tolerance factor
L	tolerance limit
m	meters
MHz	megahertz
ms	milliseconds
M	mega or 10^6
MEFE	maximum expected flight environment
n	natural or new (subscript) total number of samples
NASA	National Aeronautics and Space Administration
PF	protoflight
Q	quality factor
Qual	qualification
r	reference (subscript)
s	second sample standard deviation
SEA	statistical energy analysis
SRS	shock response spectrum
Symp.	Symposium
TM	Technical Memorandum
x	SRS magnitude
y	logarithmically transformed SRS magnitude

3.2 Definitions

3.2.1 Pyroshock

Pyrotechnic shock or pyroshock is the transient response of structural elements, components, assemblies, subsystems and/or systems to loading induced by the activation of pyrotechnic (explosive- or propellant-activated) devices incorporated into or attached to the structure. In certain cases, the pyrotechnic loading may be accompanied by the release of stored energy due to structural preload, or by impact between structural elements as a result of the explosive or propellant activation. Pyroshock-like transients may also be created by non-explosive devices where the energy comes mainly from the elastic energy release.

3.2.2 Pyrotechnic Source Categories

Pyrotechnic devices may be divided into two general categories, as follows: First, point sources; and second, line sources. Typical point sources include explosive bolts, separation nuts, pin pullers and pushers, bolt and cable cutters, and certain combinations of point sources and pyro-activated operational hardware (e.g., pyrovalves). Typical line sources include flexible linear shaped charges, mild detonating fuses, frangible joints, explosive transfer lines, and certain commercially-available products intended to fully contain explosive and structural debris during and after separation. Point and line sources may also be combined; V-band clamps use point sources which may then allow the rapid release of stored strain energy from a structural preload acting along a line of contact between two structures being separated.

3.2.3 Pyroshock Environmental Categories

In this Standard, pyroshock environments have been broadly divided into three categories, as follows: First, near-field; second, mid-field; and third, far-field. For most aerospace installations, the distinction between these three categories is the magnitude and spectral content of the environment, which depends on the type and strength of the pyroshock device, the source/hardware distance, and the configuration details of the intervening structure (especially discontinuities like joints, corners, lumped masses, and resilient elements, which can significantly attenuate the high frequency content of the pyroshock environment). The pyroshock environmental category usually has a strong influence on the hardware design and/or selection. In broad terms, these categories may be described as follows and should be used as guidelines:

a. The near-field environment is dominated by direct wave propagation from the source, causing peak accelerations in excess of 10,000 g and substantial spectral content above 10,000 Hz. In general, most line sources are very intense sources, and point sources are less intense sources. Ideally, in a good aerospace system design, there should be no pyroshock-sensitive hardware exposed to a near-field environment, so that no near-field testing will be required.

b. The mid-field environment is characterized by a combination of wave propagation and structural resonances, causing peak accelerations between 1000 and 10,000 g and substantial spectral content between 3 kHz and 10 kHz.

c. The far-field environment is dominated by structural resonances, with peak accelerations below 1000 g and most of the spectral content below 3 kHz.

3.2.4 Pyroshock Environmental Parameters

Although pyroshock may be characterized as a transient force, strain or velocity, it is almost always described in terms of an acceleration time history and its computed spectrum:

a. The time history or waveform is usually described in terms of its absolute peak acceleration and its duration. Vibration and/or electrical noise can occur simultaneously with pyroshock, which may make it difficult to ascertain the total duration. If this occurs, the 10 percent duration, defined as the time between the instant of shock arrival at the measurement point and the instant that the waveform has decayed to 10 percent of the absolute peak value, is sometimes substituted (Himelblau and Others (2006)). Temporal moments may also be used to characterize the waveform, including the duration (Cap, J.S.; Smallwood, D.O. (1997)). Two typical acceleration time-histories are shown as inserts in figures 1 and 2.

It should be noted that velocity, rather than acceleration, has been proposed by some organizations dealing with transients as the preferred response parameter, since resonant stresses have been shown to be theoretically proportional to velocity (Gaberson, H.A.; Chalmers, R.H. (1995)). The pseudo-velocity response spectrum is the recommended way to represent velocity as a response parameter for transients. ISO 18431-4 also provides this algorithm.

b. One or more of the following spectra may be computed to characterize the frequency content of a transient: Fourier, “energy,” or shock response spectra (SRS) (Himelblau and Others (2006)); (Rubin, S.; Ahlin, K. (2010)). The SRS is the one most commonly used for pyroshock environment and test description. The knee frequency is the dominant frequency in a pyroshock SRS, at which the slope for the SRS changes from an approximate + 9 dB/octave to + 12 dB/octave slope (+1.5 to +2 on a log-log plot) to an approximately horizontal slope or plateau with peaks at the major local structural frequencies. All pyroshock SRS have a knee frequency, even if not properly measured or quantified. Section 3.2.3 details the different SRS characteristics of near-field pyroshock (no knee frequency below 10,000 Hz) and mid-field and far-field pyroshock containing a knee frequency in their respective frequency ranges. *If* the hardware dominant modal properties (including damping values) are known, then the acceleration time- history and/or the SRS may be used to compute the hardware response. However, in nearly all cases, these resonant parameters are unknown or inadequately estimated, especially at the high frequencies normally associated with pyroshock, so natural frequencies are usually assumed to correspond to one-twelfth (1/12) octave band center frequencies over the frequency range of interest (see section 3.2.3) and a constant quality factor is selected as Q=10, corresponding to a fraction of critical damping of $\zeta = 0.05$. In addition, there are several different categories of SRS magnitude, including positive, negative, primary, residual, and maximax SRS (Himelblau and Others (2006)); (Rubin, S.; Ahlin, K. (2010)). The maximax SRS envelopes the previous four and is the one most commonly used for pyroshock testing. A typical maximax SRS for far-field pyroshock is shown in figure 1. The SRS acceleration is also called the maximum or peak absolute response acceleration. Typical near-field positive and negative SRS are shown in figure 2.

Both the transient time history and resulting spectrum are critical to the environmental definition and test verification.

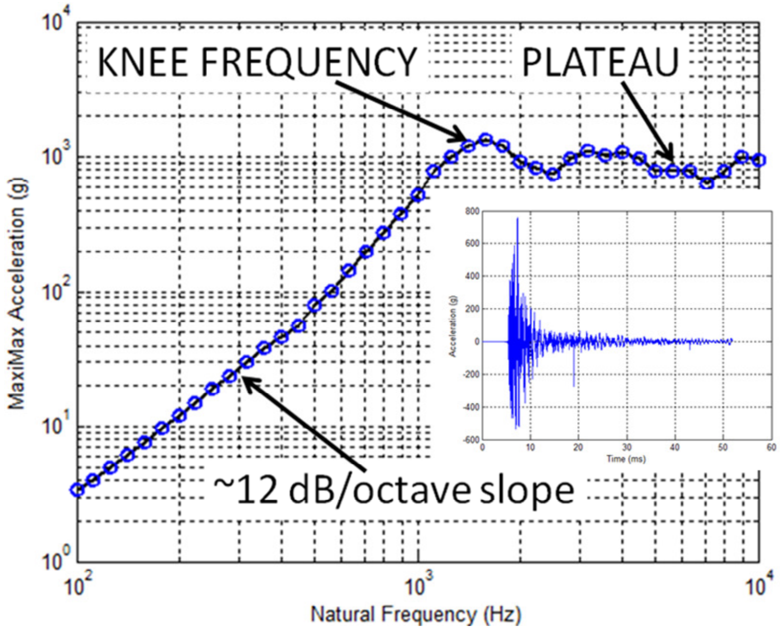

Figure 1—Typical Far-Field Pyroshock Acceleration Time History and Maximax Shock Response Spectrum

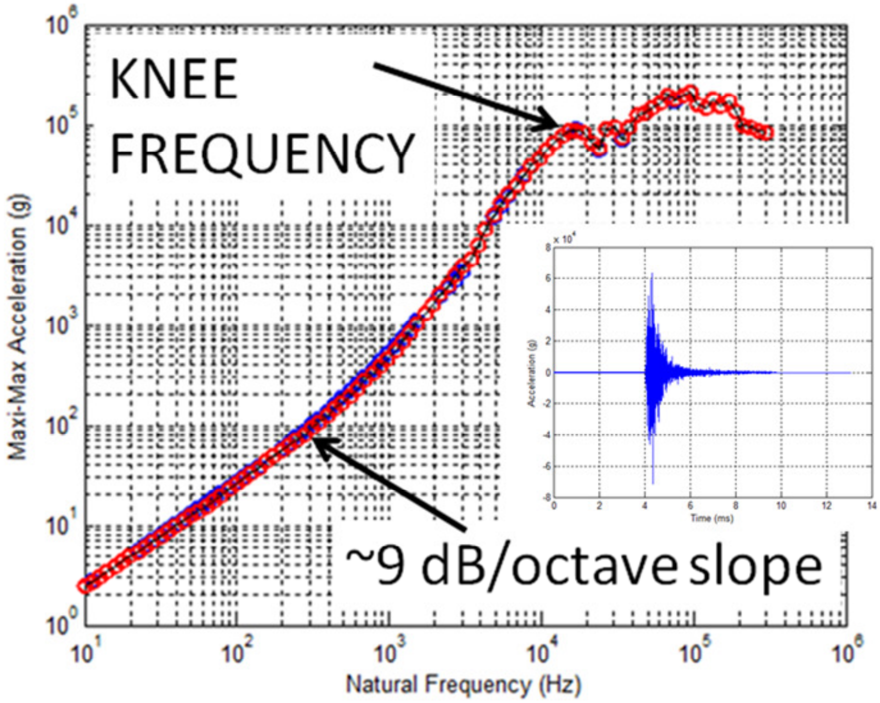

Figure 2—Typical Near-Field Acceleration Time History and Postive and Negative Shock Response Spectrum

3.2.5 Environmental Test Categories

There are four programmatic categories under which pyroshock tests are usually performed:

a. A Qual test is performed on a hardware item that will not be flown, but is manufactured using the same drawing, materials, tooling, processes, inspection methods, and personnel competency as used for the flight hardware. The purpose of a Qual test is to verify the design integrity of the flight hardware with a specific margin.

b. When performed, an FA test is conducted on a flight hardware item, including spare(s), where the hardware design integrity has already been verified by a Qual test. The purpose of an FA test is to detect workmanship errors and material defects that may have occurred during production without contributing a significant amount of additional damage to the hardware prior to flight.

c. A PF test is performed on flight hardware when there is no qualification hardware item available. The purpose of a PF test is the same as that for a Qual test, except that a PF test also satisfies the purpose of a FA test.

d. A development test may be performed on a hardware installation to ascertain environmental conditions; on a hardware item to determine its susceptibility to an environment; to verify the adequacy of an analytical model; and/or to evaluate the effects of various environmental reduction measures, usually early in a program.

The results from these test categories are used in the classification of test hardware, e.g., Qual hardware.

3.2.6 Level of Assembly Categories

One or more of the above tests may be performed on a hardware system and/or assembly. Tests performed on payloads, spacecraft, and large subsystems are commonly referred to as system-level tests, whereas those performed on electronic equipment, mechanical devices, components and small subsystems are commonly referred to as assembly-level tests. Most system-level pyroshock environments are self-induced, whereas most assembly-level pyroshock environments are externally-induced, as described in NASA-STD-7002, Payload Test Requirements. As a result, system-level tests traditionally do not incorporate margins for Qual and PF testing, but nearly always utilize flight pyrotechnic devices and flight or flight-like intervening structure. In contrast, assembly-level tests may incorporate test margins for Qual and PF testing, and utilize test structure between the shock source and the test article(s) which may or may not resemble flight structure.

4. REQUIREMENTS

In addition to the requirements that follow, this section contains additional description and guidance to the requirements in section 1.6.

4.1 Pyroshock Test Rationale

The rationale for assembly-level pyroshock testing is to provide design and/or, in some cases, workmanship verification of the assembly to withstand pyroshock loading prior to the integration of the assembly with the flight system. The rationale for system-level pyroshock testing is generally to do the following:

- *Provide design and, in some cases, workmanship verification of the assembled flight system to withstand pyroshock loading.*
- *Verify assembly-level test environments or justify the omission of assembly-level testing.*
- *Demonstrate that the hardware separates, deploys, or activates as expected after actuation of the pyrotechnic device.*

Pyroshock testing at the payload level for both externally and self-induced pyroshocks is required under NASA-STD-7002. The decision to perform or omit pyroshock testing at lower levels of assembly should be based on the following:

- *The known ruggedness or robustness of the hardware.*
- *The relative severity of the pyroshock environment compared to lower frequency dynamic environments, such as random vibration.*
- *The range of dominant hardware resonances relative to the anticipated spectral content of both lower frequency and pyroshock environments. For example, the cross-over frequency between random vibration and pyroshock severities may be as low as the following:*

- *100 Hz for near-field pyroshock.*
- *500 Hz for mid-field pyroshock.*
- *1 kHz for far-field pyroshock (Moening, C.J. (1984)).*

Small components are more likely to be susceptible to pyroshock failure in all three categories (Rubin, S.; Ahlin, K. (2010)), unless they are protected from the high frequency environment, e.g., by resilient mounts or elements.

4.1.1 If there is a question about the hardware susceptibility to pyroshock, then pyroshock testing shall be performed. *A pyroshock development test early in the flight program should be useful in determining hardware susceptibility, and avoiding the programmatic consequences of failure during Qual, FA, or PF testing later in the program.*

4.1.2 Pyroshock verification shall be accomplished by Qual and FA or PF testing.

4.1.2.1 Successful pyroshock testing shall be considered essential to mission success.

4.1.2.2 Pyroshock testing shall be performed in compliance with NASA-STD-8719.12, Safety Standard for Explosives, Propellants, and Pyrotechnics.

4.2 Maximum Expected Flight Environment

4.2.1 Pyrotechnic test criteria shall be based upon the MEFE or service environment, which may be estimated from the following:

a. A transient analysis.

b. An envelope of measured flight or ground test data.

c. A statistical analysis of these measured data.

The last alternative is preferred when there are three or more measurements.

4.2.2 When statistical analysis is selected, the MEFE shall be based on P95/50 statistics of SRS data, i.e., a 95 percent upper tolerance limit with 50 percent confidence, assuming the SRS database is log-normally distributed. *Pyroshock environmental prediction and MEFE determination, which are critical to the selection of test criteria, are described in Appendices A and B, respectively.*

4.3 Test Margins and Number of Applications

It is possible that a Qual test article would pass a specified test, and the flight hardware fails the same test conditions because of hardware strength variability. Pyroshock tests for externally-induced shock environments are usually performed by utilizing a simulation technique and flight or flight-like hardware. As a consequence, simulation of the flight shock environment can be reasonably achieved, and a test magnitude margin is generally achievable. Pyroshock test margins are summarized in table 1 of section 1.6.

4.3.1 Pyroshock Qual testing for externally-induced pyroshock environments shall be performed with a magnitude margin added to the MEFE to account for failure due to hardware variability. Furthermore, a fatigue or time-dependent margin is also added to cover potential cyclic failure modes.

4.3.1.1 A minimum Qual margin of 3 dB (or 1.4 x MEFE) shall be added to the MEFE uniformly across the spectrum for pyroshock Qual testing.

4.3.2 A minimum of two shock applications per axis for externally-induced shock environments shall be applied for pyroshock Qual testing.

4.3.3 When performed, FA testing for externally-induced shock environments shall be conducted at MEFE conditions with a minimum of one shock application per axis.

4.3.4 PF testing for externally-induced shock environments shall be performed at Qual magnitude (or 1.4 x MEFE) with one application per axis.

Pyroshock tests for self-induced shock environments are usually performed by utilizing flight pyrotechnic devices and flight or flight-like structure. As a consequence, duplication of the flight shock environment can be reasonably achieved, but a test magnitude margin is generally unachievable.

4.3.5 For Qual and PF testing for self-induced shocks, a minimum of two firings of the flight pyrotechnic devices shall be performed for those devices that generate the dominant pyroshock environment for potentially sensitive equipment. *In cases where multiple pyrotechnic devices are used during flight, it is common practice to perform multiple firings of only the pyrotechnic device(s) generating the worst-case shock environment.*

4.3.6 For devices that do not generate the dominant pyroshock environment for potentially sensitive equipment, the pyrotechnic devices shall be fired once to verify that they do not generate a more severe shock condition for any potentially susceptible hardware.

4.3.7 When FA testing is performed for self-induced shocks, one firing of the flight pyrotechnic devices shall be performed for those devices that generate the dominant pyroshock environment for potentially sensitive equipment.

4.4 Test Specifications

Pyroshock tests for self-induced pyroshock environments are usually performed by utilizing flight pyrotechnic devices and flight or flight-like structures. The most flight-like pyroshock simulation is achieved using actual pyrotechnic devices and flight structure which incorporate all configuration details. Where practical, pyrotechnic devices used should be identical to devices used in the end item, including use of explosive or propellant materials from the same manufacturing lot. However, it is generally not practical to add a qualification magnitude margin for system-level firing of pyrotechnic devices, thus the criteria for data acquisition and data analysis in sections 4.6 and 4.7 should be closely followed to properly verify assembly-level test environments. System-level testing for self-induced shocks also provides an opportunity to verify the operation of the pyrotechnic subsystem, including the flight firing circuitry. In all cases, care is to be exercised to avoid the inadvertent firing of a pyrotechnic device (NASA-STD-8719.12).

System-level test firings of pyrotechnic devices can have a significant impact on project resources. For instance, the removal and replacement, as well as structural refurbishment, of pyrotechnic line source devices subsequent to test firings can be expensive and schedule consuming. Likewise for point sources located within operational systems, e.g., pyrovalves, the cost of their replacement, as well as system cleanout and refurbishment, may be considerable. For these reasons, projects sometimes compromise the system-level pyrotechnic device firing program by eliminating multiple firings of some devices or by performing firings of some devices only on a development hardware subsystem.

4.4.1 System-level pyrotechnic device firings shall be adequately instrumented to verify assembly level requirements.

Pyroshock test specifications for externally-induced shock environments vary widely depending on the test methods and facilities utilized and the characteristics of the pyroshock environment, which are categorized in section 3.2.3 as near-, mid- and far-field.

4.4.2 Pyroshock tests for externally-induced environments shall be specified using the maximax SRS with a constant quality factor of Q=10, based on the MEFE described in section 4.2 and a margin described in section 4.3, over a natural frequency range from a low frequency limit of 100 Hz (or less) to a high frequency limit of 100 kHz (or more) for near-field environments; 10 kHz (or more) for mid-field environments; and 3 kHz (or more) for far-field environments, unless the measured spectral content of the externally-induced shock shows that a somewhat restricted range is adequate.

4.4.3 The pyroshock test to simulate externally-induced environments shall achieve the required SRS within the tolerances of section 4.8 for three orthogonal axes.

4.4.3.1 As discussed in section 3.2.4, a constant quality factor of Q=10 shall be utilized.

4.4.4 The pyroshock test waveform or time history shall have similar oscillatory characteristics to that of the predicted flight event, e.g., several frequency-dependent decaying sinusoids occurring simultaneously.

4.4.4.1 The total pyroshock duration shall also be similar to that of the predicted flight event and no longer than 20 ms.

4.4.5 As discussed in section 3.2.3, pyroshock-sensitive hardware should be located so that it is not exposed to the near-field environment. However, if this recommendation cannot be followed, near-field testing shall be required. *Because of the high accelerations and high spectral content found in the near-field, the choice of test methods and facilities is limited, and measurements of the shock environment are difficult.*

4.5 Test Methods and Facilities

Depending upon which of the three pyroshock environmental categories listed in section 3.2.3 applies to the hardware, pyroshock testing for externally-induced shock environments may be achieved by using one of the following types of sources:

- *A pyrotechnic device (Bement, L.J.; Schimmel, M. (1995); IEST-RP-DTE032.2 (2009)).*

- *A mechanical impact device comprising the impact of one structural member (e.g., a hammer) upon another (e.g., a beam, plate, shell, or combinations thereof) (IEST-RP-DTE032.2 (2009); Bateman, V.I.; Davie, N.T. (2010)).*

- *A vibration exciter or shaker programmed to generate short duration transient motion (IEST-RP-DTE032.2 (2009); Bateman, V.I.; Davie, N.T. (2010); Luhrs, H.N. (1976)).*

If the hardware is to be exposed to near-field pyroshock, usually only a pyrotechnic device may be used. For hardware in the mid-field, both impact and pyrotechnic devices are used. For hardware in the far-field, all of these devices are used. It's important to stress that use of actual pyrotechnic devices with flight or flight-like structures will always produce the most accurate simulations. However, the value of early qualification or protoflight testing for potentially susceptible hardware and the cost of true flight simulations may make the alternative test methods very attractive.

The most common pyrotechnic device for simulation of near-field externally-induced shock environments is linear, flexible detonating charges attached to the edges or backside of a steel plate, with the test article mounted on the plate in the same manner as it is in actual usage (IEST-RP-DTE032.2 (2009); Bateman, V.I.; Davie, N.T. (2010)). The advantage of this shock test technique and various custom pyrotechnic source shock test techniques is their ability to achieve the high accelerations and high frequencies characteristic of the near-field pyroshock environment. However, they have several distinct disadvantages; namely, a sometimes lengthy trial and error period to finalize the test configuration, the various safety issues associated with explosives, and a potentially large test-to-test variation in the shock.

There is a variety of custom and commercially-available impact device shock simulators (IEST-RP-DTE032.2 (2009); Bateman, V.I.; Davie, N.T. (2010)). Most of these devices utilize a fixture or structure which is excited into resonance by a mechanical impact from a pendulum hammer, a pneumatic piston, a projectile, etc. These devices normally require a fair amount of trial and error to adjust the shock spectrum shape to the requirement. In order to reduce the trial and error time, some impact devices (tuned resonant fixtures and tunable resonant fixtures) are designed so that the resonant fixture response matches a specific SRS shape requirement or a series of SRS shape requirements (IEST-RP-DTE032.2 (2009); Bateman, V.I.; Davie, N.T. (2010)). A major advantage of most of the impact devices is their relatively low operational cost and predictable behavior, which is important in planning their utilization, but they have a somewhat limited spectral capability. In a few specific cases, a high intensity impact device may be substituted for a pyrotechnic device to achieve the desired near-field peak acceleration if it can be demonstrated that the time history and spectral content is comparable at high frequencies, e.g., above 10 kHz.

Electrodynamic shakers have the advantage of general availability, low operational cost and known controllability, but they have limited magnitude, spectra, and directional capability. In both cases, the specific spectral capacity is highly dependent on the particular design of the device. A vibration shaker may be able to achieve a shock magnitude that reaches into the lower portion of the mid-field region, but would probably be unable to achieve the desired mid-field spectral content, since most electrodynamic shakers are unable to provide sufficient excitation above 3 kHz.

Many impact devices and all vibration shakers, together with their intervening structures, are capable of generating controlled transient excitation in a single axis. In these cases, testing will nearly always need to be repeated in the other two orthogonal axes. However, it should be noted that the use of vibration shakers and some impact devices may simultaneously cause under- and over-testing: under-testing due to uniaxial excitation compared to the triaxial service environment; over-testing due to a massive shaker table and fixture compared to the service installation, plus accelerometer control in the case of a shaker, without considering the lower structural impedance found in most flight installations. In addition, to avoid hard-bottoming the shaker at its displacement limits, the total velocity change from the beginning to the end of the transient must be zero.

Typical assembly-level pyroshock tests for externally-induced shock environments may utilize any of the above test techniques; however, there are practical limitations on the size and weight of the test article. For systems and some large assemblies, it may be necessary to utilize the flight or flight-like pyrotechnic device for the externally-induced shock environment, with intervening flight or flight-like structure. For example, separation from the launch vehicle is often a significant shock source for a spacecraft, yet the pyrotechnic separation device, such as a V-band clamp, and the intervening structure, such as a payload adapter fitting (PAF), is provided by the launch vehicle. In these cases, it is common practice for the spacecraft organization to borrow a V-band clamp and test PAF from the launch vehicle organization for pyrotechnic shock testing of the spacecraft.

Pyroshock tests for self-induced shock environments are usually performed on flight hardware by firing flight pyrotechnic device(s) and utilizing flight or flight-like structure, as discussed in sections 4.3 and 4.4. If the test involves the deployment of an operational system, e.g., antennae or solar panels, the test facility is to be designed or modified to accommodate the deployment or restrain it, as required. In cases where the flight deployment occurs in space, an altitude chamber may be the required test facility.

4.6 Data Acquisition

Pyroshock tests are nearly always instrumented for the purpose of environmental evaluation and/or test control. Pyroshock measurements are normally made with accelerometers despite some potentially serious deficiencies. Often in the near-field and sometimes in the mid-field, improperly selected accelerometers break, hard bottom, or saturate under pyroshock loading and/or incorrectly-set signal conditioners may saturate if accelerometer resonances are sufficiently excited (Himelblau and Others (2006)). If great care is not exercised, these nonlinear responses can make the resulting data invalid over the entire spectrum. This problem can usually be avoided by ensuring that the natural frequency of the accelerometer significantly exceeds the frequency range of the pyroshock environment (e.g., by at least a factor of five, unless the accelerometer resonances are highly damped (Himelblau and Others (2006)). Accelerometers should be selected for the anticipated pyroshock environment defined in section 3.2.3, as well as other conditions, with a higher natural frequency and a lesser sensitivity usually required in the near- and mid-fields (Himelblau and Others (2006)). In recent years, two accelerometer developments have permitted improved pyroshock measurement quality as follows:

- *Piezoresistive accelerometers having natural frequencies in excess of 1 MHz and shock limits of 200,000 g.*

- *Accelerometers with built-in or attached shock isolators or mechanical filters (Himelblau and Others (2006)).*

Unless care is exercised in their selection, accelerometers located on flexible structures may erroneously generate electrical signals caused by base bending (Himelblau and Others (2006)). In the high frequency range (over 2 kHz) the measured response can be very localized, and a few inches difference can make a big change in the high frequency content. A noise gage, an inert accelerometer or an accelerometer not attached to the unit under test, is highly recommended (Himelblau and Others (2006); IEST-RP-DTE032.2 (2009)).

In general, the requirements for pyroshock data acquisition are more stringent than data acquisition for other environments, such as mechanical shock or vibration. The data acquisition system should be selected or adjusted so that the maximum anticipated instantaneous signal from the accelerometer is sufficiently less than the system linear magnitude capability, thus providing adequate dynamic range where slew rate capability is important (Himelblau and Others (2006); Hollowell, B.; Smith, S. (1991)). In the near field, it is recommended that the accelerometers, and their mounting blocks when used, be attached to the structure with both bolts and special adhesive (Himelblau and Others (2006); Hollowell, B.; Smith, S. (1991)). Inplane measurements *usually require mounting blocks and often the special installation of accelerometer pairs to allow for the separation of inplane and rotational responses.*

Accelerometer problems can sometimes be avoided by using velocity pickups or, in laboratory ground tests, by using laser Doppler vibrometers instead of accelerometers, although these instruments also have some potentially serious deficiencies (Himelblau and Others (2006); Valentekovich, V.M.; Goding (1990); Litz, C.J. (1997)). Strain gages have also been promoted as replacements for accelerometers, since strain transducers have no resonances, but simply respond dynamically with the structure to which they are attached (Bement, L.J.; Schimmel, M.L. (1995); Evans and Others (1987)). Unfortunately, most aerospace structures are highly non-uniform with large numbers of spatially-varying stress concentrations. Under these circumstances, even small changes in gage location could cause large changes in measured strain data. In addition, at high frequencies and short wavelengths normally associated with pyroshock, measured strain can also change substantially by a simple change in gage grid size (Himelblau and Others (2006)).

In sections 4.4.2 - 4.4.4, SRS frequency ranges are recommended for near-, mid- and far-field tests, respectively, unless the measured spectral content shows that a more restricted range is adequate. Near the low frequency limit, a restricted frequency range may be used if the SRS from an ambient vibration environment or electrical noise floor equals or exceeds the measured pyroshock SRS. Near the high frequency limit, the absolute peak acceleration of the time history should equal or approximate the measured pyroshock SRS, called the zero period response acceleration (Himelblau and Others (2006)).

When digital data acquisition and/or analysis are utilized, the digital sampling rate should equal or exceed 10 times the highest SRS natural frequency.

4.6.1 Before ADC, anti-aliasing filters shall be applied to the analog signals. *Above the filter cutoff frequency, an attenuation slope of 60 dB/octave (or equivalent) is recommended, and the filter cutoff frequency should be at least an octave below the Nyquist frequency. (Himelblau and Others (2006); IEST-RP-DTE032.2 (2009).)*

Other major sources of instrumentation errors should also be avoided (Himelblau and Others (2006)). Because of the high frequency limitations of most tape recorders, it is recommended that critical pyroshock data be acquired with direct-to-digital memory recorders, especially for near- and mid-field measurements. Once valid electrical signals are acquired, data analysis is then required to provide the desired acceleration time-histories and SRS's specified in section 3.2.4.

4.7 Data Analysis

Care must be taken to ensure that data acquisition errors, e.g., an imperceptible zero shift in an acceleration time history from a piezoelectric accelerometer, do not cause substantial errors in the resulting computed SRS's during subsequent data analysis (Evans and Others (1987)). The Powers-Piersol procedure is recommended for determining the validity of pyroshock data, where the single and/or double integration of the acceleration time history and the comparison of positive and negative SRS's are computed (see Himelblau and Others (2006), sections A.3.4 - A.3.5). Even the SRS computational algorithm may cause an appreciable effect on the resulting spectrum (Smith, S.; Melander, R. (1995); Smith, S.; Hollowell, B. (1996)). To reduce SRS algorithm-induced variability, the use of an SRS algorithm based on ISO 18431-4:2007 is recommended .

4.8 Test Control Tolerances

Pyroshock tests that utilize pyrotechnic devices usually have no specific tolerance control. Multiple shocks are often applied to account for firing-to-firing variations, as suggested in sections 4.3 - 4.5. For impact devices, control tolerances are often a function of the specific device and its maintenance. When shakers are used for pyroshock simulation, the most common tolerance is ± 3 dB.

4.8.1 The tolerances most commonly used in current aerospace practice are specified for the maximax SRS and shall be used:

Natural Frequency	Tolerance
$f_n \leq 3$ kHz	±6 dB
$f_n > 3$ kHz	+9/-6 dB

4.8.1.1 The SRS shall be calculated with a resolution of at least one-sixth (1/6) octave band for the natural frequency range of the test specification.

4.8.1.2 At least 50 percent of the SRS magnitudes shall exceed the nominal test specification.

4.8.1.3 The acceleration time history used to create the SRS for the laboratory pyroshock simulation shall be preserved for comparison to the flight acceleration time history.

4.9 Test Article Operation

The test article may or may not be electrically powered and operational during the pyroshock event. For assembly-level testing, power is sometimes applied, even when the hardware is unpowered during the flight event, to detect intermittent failures. For system-level power-on testing, the operational mode applicable to the flight pyrotechnic event is usually monitored.

4.10 Test Tailoring

Sufficient flexibility is provided in this Standard to satisfy the need for test tailoring in most cases. For example, utilization of a pyrotechnic device plus flight or flight-like intervening structure, instead of a shaker and some simple fixturing and intervening structure, in a mid- or far-field test should provide the correct driving-point impedance and therefore the appropriate transient force at the structure/test article interface(s), which would accomplish the same goal as force limiting in a random vibration test.

APPENDIX A

PREDICTION OF PYROSHOCK ENVIRONMENTS

There are three general ways to predict or estimate the response at various locations on a structure induced by a pyrotechnic device as follows:

a. Analytical models.
b. Direct measurements.
c. Extrapolations from previous measurements.

A.1 Analytical Models

Various analytical models have been developed over the years that are designed to predict, at least crudely, the response of aerospace structures to the transient loads produced by certain types of pyrotechnic devices. Hydrocodes have recently been used to model, in the time domain, the details of the explosive or propellant ignition and burning process, and nonlinear structural deformation and separation using Lagrangian and/or Eulerian meshes, as well as the generation and propagation of structural waves, all of which are necessary for pyroshock prediction (Hancock, S.L. and Others (1989); Goldstein, S. and Others (1995); Frey, J.D. and Others (1993)). Unfortunately, the implementation of hydrocode analysis usually necessitates high labor and computer costs.

Sometimes hydrocode models are coupled with finite element method (FEM) or statistical energy analysis (SEA) models to transfer the pyroshock energy into the mid- and far-fields. However, most FEM models are restricted to frequency ranges that are too low to be useful for pyroshock response predictions, or so spatially limited that only simple structural configurations can be accurately modeled. On the other hand, SEA was developed to predict mid frequency vibroacoustic response, modeling the structure in terms of modal groups using spatial and spectral averaging. These models have been extended to predict high frequency pyroshock response (Manning, J.E.; Lee, K. (1968); Lee, Y.A.; Henricks, W. (1992); Singh, A.K. (1993); Dalton and Others (1995)). Thus, SEA is better suited for high frequency pyroshock prediction, since structural modal density (i.e., the number of structural modes per unit bandwidth) needed for spectral averaging is roughly proportional to frequency. In fact, the sparsity or absence of low frequency modes limits SEA applications to mid and high frequencies only. Because SEA uses spatial and spectral averaging, it cannot be used to predict pyroshock response at specific locations or frequencies.

At this time, there is very limited experience to assess or recommend the use of such models. However, if an analytical model is available or has been formulated and checked against pyroshock measurements in the laboratory on specific structures with pyrotechnic devices of interest, and has been found to produce reasonably accurate results, then that model can be used to make preliminary pyroshock predictions. However, all such predictions should be verified and updated as soon as actual pyroshock data become available.

A.2 Direct Measurements

In many cases, direct measurements can be made of the responses at critical locations on the spacecraft structure induced by pyrotechnic devices, either in flight or in the laboratory. In either case, the measurements should be acquired and analyzed in accordance with the recommended practices detailed in Himelblau and Others (2006). It should be noted that lot-to-lot variations in the manufacture of pyrotechnic explosives and propellants can cause a significant variability in shock generation. Before these measurements are utilized, the quality of the data should be ascertained based on the data acquisition and analysis criteria provided in sections 4.6 and 4.7.

A.2.1 Measurements on the Vehicle in Flight

For some spacecraft, more than one assembly is manufactured because the same spacecraft design will be used for more than one flight. In this case, measurements may be made on the first flight of that design to establish the response of the structure at critical locations due to all flight pyrotechnic events. The advantage of this approach is that it provides the most accurate pyroshock predictions for later flights of that design. The primary disadvantages are as follows:

a. The procedure applies only to updating predictions after the first flight and, hence, cannot be used to establish initial test requirements for the spacecraft or its components.

b. Flight pyroshock measurements are expensive to acquire.

A.2.2 Measurements on the Vehicle in the Laboratory Prior to Flight

Certain types of pyrotechnic devices can be activated and replaced without doing permanent damage to the spacecraft or its structure, e.g., propellant-activated valves. In this case, measurements may be made on the vehicle in the laboratory prior to flight to establish the response of the structure at critical locations due to the activation of these devices. The advantage of this approach is that it can provide a reasonably accurate pyroshock prediction for that specific spacecraft during flight. The primary disadvantages are as follows:

a. The procedure allows the determination of the pyroshock environment due only to a limited number of pyrotechnic devices.

b. It may be expensive to replace the activated pyrotechnic devices and recondition the spacecraft for flight.

Pyrotechnic devices are usually designed or selected to generate more than enough source energy to cause structural separation. The excess energy normally causes a shock or blast wave in the atmosphere or (partial) vacuum adjacent to the structure, with the wave magnitude increasing with the amount of excess energy and static pressure, unless the separation system is designed to contain the blast as well as the explosive or propellant debris. If flight separation occurs at altitude or in space, the atmospheric-coupled blast wave during the laboratory test can be more severe than flight conditions, unless the blast and debris are contained. If this wave is not diverted away from the structure, then an over-prediction of the flight pyroshock environment may result. However, for small amounts of excess energy, the separation process usually controls the pyroshock environment.

A.2.3 Measurements on a Prototype Vehicle in the Laboratory

Some spacecraft programs involve the manufacture of a prototype of the spacecraft design that is used for various laboratory tests, including shock and vibration tests, prior to the launch of a flight assembly. Because the activation of pyrotechnic devices sometimes alters the spacecraft structure, pyroshock measurements on prototypes are usually made after all other tests are complete. The advantages of a prototype test are as follows:

a. It can provide a reasonably accurate pyroshock prediction prior to the flight of all spacecraft of that design.

b. The prediction is achieved without jeopardizing the structural integrity of the flight article.

c. No reconditioning of flight hardware is required.

d. The operability of pyroshock devices and structural separation can be demonstrated following environmental exposure.

The primary disadvantage is that the program must provide for the manufacture of a prototype vehicle that will be available for pyroshock testing. The problem of an excessive atmospheric shock wave is the same as that discussed in section A.2.2.

A.2.4 Measurements on a Dynamically Similar Structure in the Laboratory

If a spacecraft program does not involve the manufacture of a prototype, it may still allow the construction of a dynamically similar model of at least those subassemblies that incorporate pyrotechnic devices, or such a dynamically similar model might be available from a previous spacecraft program. The advantages of a test using a dynamically similar model are as follows:

a. It may provide moderately accurate predictions of pyroshock environments, depending on how closely the model dynamically represents the spacecraft of interest.

b. The prediction is achieved without jeopardizing the structural integrity of the flight article.

c. No reconditioning of flight hardware is required.

The primary disadvantage is that the program must provide for the manufacture of a dynamically similar model, or an appropriate model must be available from a previous program. The problem of an excessive atmospheric shock wave is the same as that discussed in section A.2.2.

A.3 Extrapolations from Previous Measurements

A vast amount of pyroshock data has been acquired and analyzed over the years for many spacecraft programs, both in the laboratory and in flight, e.g., (Kacena and Others (1970); Spann and Others (1982, 1993)). Even though the data may have been acquired for totally different spacecraft designs and different pyrotechnic devices, at least crude estimates for the pyroshock environment to be expected on a new spacecraft design can be determined by extrapolations from measurements on a previous spacecraft of different design, commonly referred to as the reference spacecraft. Of course, the closer the design details of the new and reference spacecraft, the more accurate the extrapolations. Also, the most accurate extrapolations are provided when the pyroshocks on the new and reference spacecraft are caused by the same type of pyrotechnic device. However, before these data are utilized, the quality of these data should be ascertained based on the data acquisition and analysis criteria provided in sections 4.6 and 4.7.

Extrapolation procedures for pyroshock environments generally involve two primary scaling operations as follows:

a. Scaling for the total energy released by the pyrotechnic device.

b. Scaling for the distance and structural configuration between the pyrotechnic energy source and the response location of interest.

Sometimes scaling for the surface weight density of the structure is also employed, but such extrapolations usually are not effective because the intense compressive waves generated by pyroshocks are not strongly influenced by surface weight density. Based upon procedures in (Kacena and Others (1970); Spann and Others (1982, 1993)), the following scaling rules for source energy and distance from the source are recommended.

A.3.1 Source Energy Scaling

Letting E_r and E_n denote the total energy released by the pyrotechnic device on the reference and new spacecraft, respectively, the shock response spectrum at all frequencies is scaled from the reference vehicle to the new vehicle by

$$SRS_n(D_1) = SRS_r(D_1)\sqrt{\frac{E_n}{E_r}} \qquad (A.1)$$

where SRS_r and SRS_n are the shock response spectra for the reference and new spacecraft, respectively, at the same distance D_1 from the pyrotechnic source. Caution should be exercised in the utilization of Equation (A.1). In many cases, an excess of source energy beyond that required to cause structural separation will not increase the shock transmission, but instead will generate an increased shock or blast wave that will be transmitted into the atmosphere or (partial) vacuum adjacent to the structure. This excess energy may not be as effective in generating structural response. Thus, when $E_n > E_r$, the application of Equation (A.1) may cause an over-prediction of the pyroshock environment. Similarly, an under-prediction may result when $E_n < E_r$.

A.3.2 Source to Response Location Distance Scaling

A number of empirically derived scaling relationships to correct the magnitude of pyroshock environments for distance from a pyrotechnic source to a response location of interest have been proposed over the years (Kacena and Others (1970); Spann and Others (1982, 1993)). One set of scaling curves for typical pyroshocks propagating through various types of structure, as developed in (Kacena and Others (1970), is summarized in figure 3. Note the results in figure 3 apply to the peak value of the pyroshock response.

Another scaling relationship for the shock response spectrum produced by point sources on complex structures is given by

$$\mathrm{SRS}(D_2) = \mathrm{SRS}(D_1)\exp\left\{\left[-8\times 10^{-4} f_n^{\left(2.4 f_n^{-0.105}\right)}\right]\left[D_2 - D_1\right]\right\} \qquad \text{(A.2)}$$

where D_1 and D_2 are the distances in meters from the pyrotechnic source to the reference and new locations, respectively, on the spacecraft, and $\mathrm{SRS}(D_1)$ and $\mathrm{SRS}(D_2)$ are the shock response spectra for the responses at the reference and new locations, respectively.

Since Equation (A.2) predicts an SRS, the results are a function of the SRS natural frequency. Plots of Equation (A.2) for various values of $\delta D = D_2 - D_1$ are shown in figure 4.

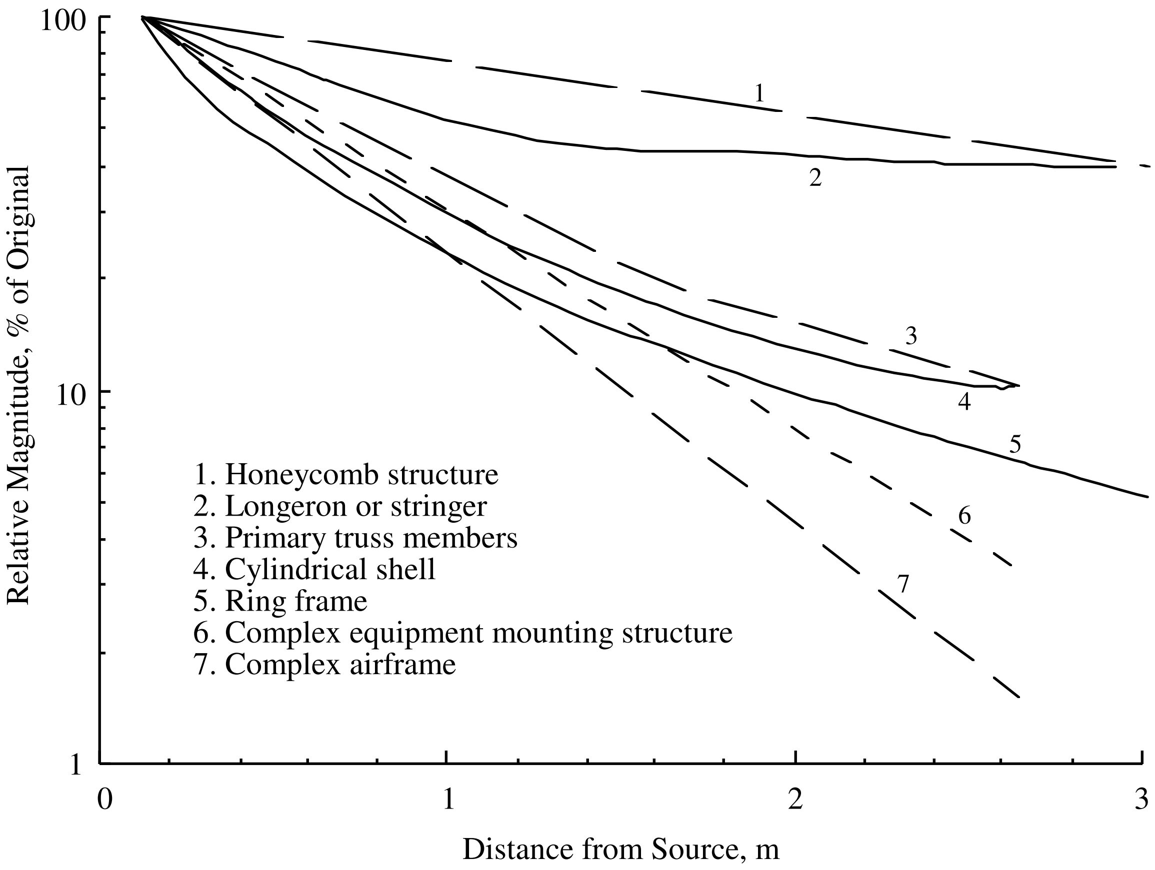

Figure 3—Peak Pyroshock Response versus Distance from Pyrotechnic Source

It is important to note that Equation (A.2) was derived from pyroshock data produced by a point source on complex structure at sea level, and may not be representative of other sources and structures in space, as discussed in sections A.2.1 and A.2.2. Other source scaling rules may be developed from data for sources and structures more like those associated with a specific spacecraft, which may be substituted for the results in figures 3 and 4 (Keegan, W.B.; Bangs, W.F. (1972)).

As a final point concerning the attenuation of pyroshocks with distance, there is usually a substantial reduction in pyroshock magnitudes due to transmission across structural joints. Specifically, Kacena and Others (1970) suggest that the attenuation due to structural joints ranges from 20 to 75 percent, depending on the type of joint and the manner in which it changes the shock transmission path. On the other hand, others suggest a 50 percent reduction for a major discontinuity and 30 percent per normal joint up to a maximum of three joints and no attenuation for the up-ramp portion of the SRS. Other joint attenuation data that may be available from prior experience (e.g., (Spann and Others (1982, 1993)) should also be considered, as applicable.

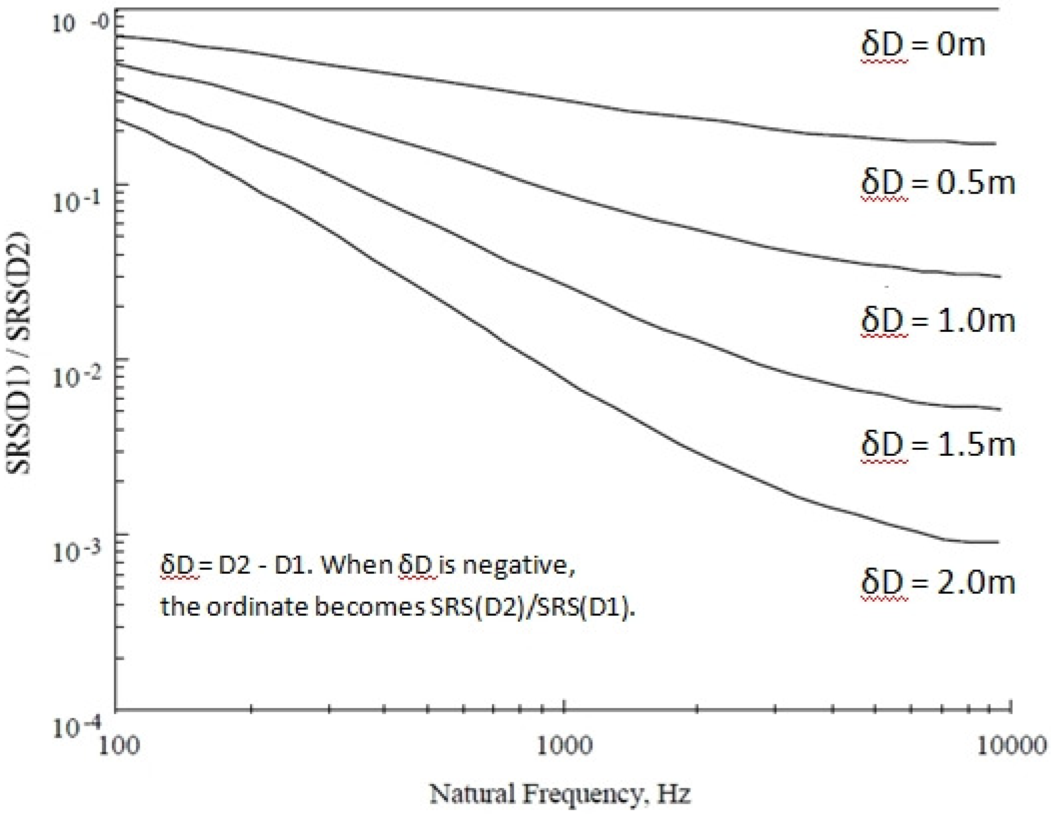

Figure 4—Correction of Shock Response Spectrum for Distance from Pyrotechnic Source

APPENDIX B

DETERMINATION OF MAXIMUM EXPECTED FLIGHT ENVIRONMENT

The prediction procedures detailed in Appendix A generally yield the SRS at individual points on the structure that do not necessarily correspond to all the points of interest in the formulation of pyroshock test criteria. Furthermore, the predictions may be based upon estimated or measured pyroshocks that do not reflect the potential variations in the pyroshock environments produced by different pyrotechnic devices of the same type. Hence, it is necessary to convert the predicted pyroshock magnitudes into a single SRS, referred to as the "maximum expected flight environment," that will account for point-to-point (spatial) and event-to-event variations. The computation of the maximum expected flight environment involves the following two steps:

a. The division of the predictions for a specific pyrotechnic event into groups with similar SRS values, referred to as "zones."

b. The selection of a conservative upper bound on the SRS values in each zone, referred to as a "zone limit," which constitutes the maximum expected flight environment for that zone due to that specific pyrotechnic event.

B.1 Determination of Zones

The SRS magnitudes for the structural responses due to a single pyrotechnic event typically vary widely from one location to another, particularly as the number of joints and/or the distance from the pyrotechnic source increases. The goal in zoning is to divide the spacecraft structure into regions or zones such that the responses at all points within each zone due to a single pyrotechnic event are reasonably homogeneous, meaning the SRS magnitudes for the responses at all points within each zone can be described by a single SRS that will exceed most or all of the SRS magnitudes at the individual points without severely exceeding the SRS magnitude at any one point. It is also required that the selected zones correspond to structural regions of interest in the formulation of test criteria, e.g., a single zone should include all the attachment points for a single component, and preferably for several components, that must be tested for the pyroshock environment.

The zoning operation is usually accomplished based upon engineering judgment, experience, and/or a cursory evaluation of predicted SRS magnitudes. For example, engineering judgment dictates that frame structures and skin panels should represent different zones, since the response of skin panels will generally be higher than the much heavier frames. Also, experience suggests that the structural regions in the near-field and far-field of the pyrotechnic source have widely different SRS's and should represent different zones. Beyond such engineering considerations, a visual inspection of the SRS magnitudes for the predicted pyroshocks can be used to group locations with SRS's of similar magnitudes to arrive at appropriate zones.

It is assumed that the available SRS's for a given zone are predicted at locations that are representative of all points of interest in that zone. Ideally, this would be achieved by a random selection from all possible response points within the zone. In practice, a random selection usually is not feasible since the predictions are commonly made before the zones are selected; in fact, the spectra for the predicted responses are often used to establish the zones, as discussed above. In some cases, however, the predictions may be made at those points where a component of interest is mounted. This would constitute a good selection of response points, even though such mounting points might not be representative of all points within the zone. In any case, it is important to assess the locations represented by the available predicted pyroshocks to assure that they are typical of all points of interest in the zone.

B.2 Computation of Zone Limits

A conservative limit for the predictions at various points within a zone may be determined using any one of several procedures (Piersol, A.G. (1994, 1996)). The simplest procedure is to envelope the available SRS's, with the amount of conservatism based on the quantity and quality of the data. However, the procedure recommended here is to compute a normal tolerance limit that covers the SRS magnitudes for at least 95 percent of the locations in the zone with a confidence coefficient of 50 percent, referred to as the P95/50 limit (Owen, D.B. (1963)). Specifically, given n measurements of a random variable x, an upper tolerance limit is defined as that value of x (denoted by L_x) that will exceed at least β fraction of all values of x with a confidence coefficient of γ. The fraction β represents the minimum probability that a randomly selected value of x will be less than L_x; the confidence coefficient γ can be interpreted as the probability that L_x will indeed exceed at least β fraction of all values of x. Tolerance limits are commonly expressed in terms of the ratio, $(100\beta)/(100\gamma)$, e.g., the P95/50 normal tolerance limit represents $\beta = 0.95$ and $\gamma = 0.50$. In the context of pyroshock predictions, x represents the SRS value at a specific frequency for the response of the spacecraft structure at a randomly selected point within a given zone, where x differs from point-to-point within the zone due to the spatial variability of the response. However, x may also differ due to other factors, such as variations from one pyroshock to another produced by the same type of pyrotechnic device. In selecting a sample of predicted SRS magnitudes to compute a tolerance limit, beyond the SRS values at different locations within a zone, it is wise to include SRS magnitudes from different spacecraft of the same design, if feasible, so that sources of variability due to location and firing-to-firing are represented in the measured or predicted SRS values.

Tolerance limits are most easily computed when the random variable is normally distributed. The point-to-point (spatial) variation of the pyrotechnically induced responses of spacecraft structures is generally not normally distributed, but there is empirical evidence that the logarithm of the responses from pyroshock as well as random vibration does have an approximately normal distribution (Himelblau and Others (2006); Barrett, S. (1975)). Hence, by simply making the logarithmic transformation

$$y = \log_{10} x \tag{B.1}$$

where x is the SRS magnitude at a specific natural frequency of the response within a zone, the transformed variable y can be assumed to have a normal distribution. For n sample values of y, a normal tolerance limit is given by

$$L_y = \bar{y} + k_{n\beta\gamma}\, s_y \qquad \text{(B.2)}$$

where y is the sample average and s_y is the sample standard deviation of the n transformed spectral values computed as follows:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \quad ; \quad s_y = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \qquad \text{(B.3)}$$

The term k in Equation (B.2) is called the normal tolerance factor, and is a tabulated value; a tabulation of k for β = 0.95 and γ = 0.50 is presented in table 2, which is taken directly from (Owen, D.B. (1963)). The normal tolerance limit for the transformed variable y is converted back to the original engineering units of x by

$$L_x = 10^{L_y} \qquad \text{(B.4)}$$

To simplify test criteria, normal tolerance limits are often enveloped and smoothed using the tabular data below. (See NASA-HDBK-7005, Dynamic Environment Criteria, for further details.)

Table 2—Tolerance Factors for P95/50 Normal Tolerance Limit

n	3	4	5	6	8	10	15	20	30	50	∞
$k_{n,\beta,\gamma}$	1.94	1.83	1.78	1.75	1.72	1.70	1.68	1.67	1.66	1.65	1.64

APPENDIX C

GUIDANCE

C.1 Purpose and/or Scope

The purpose of this Appendix is to provide guidance and is made available in the reference documents listed below.

C.2 Reference Documents

C.2.1 Government Documents

ISO 18431-4:2007. Mechanical vibration and shock - Signal processing - Part 4: Shock-response spectrum analysis.

NASA-HDBK-5013. Pyrovalve Applications and Performance Handbook

Bement, L.J.; Schimmel, M.L. (June 1995). "A Manual for Pyrotechnic Design, Development and Qualification," NASA TM 110172.

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C.2.2 Non-Government Documents

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