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National Aeronautics and
Space Administration

NASA-STD-7003
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PYROSHOCK TEST CRITERIA

NASA TECHNICAL STANDARD

FOREWORD

This Standard is approved for use by NASA Headquarters and all NASA Centers and is intended to provide a common framework for consistent practices across NASA programs.

The NASA Office of Chief Engineer has implemented a program to develop NASA-wide benchmark standards to encourage the use of best practices and to support consistent treatment of engineering issues across the Agency. 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. This standard provides 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. This standard was prepared by the Jet Propulsion Laboratory for the NASA Chief Engineer's Office.

To ensure successful operation of systems using pyrotechnic devices, the best approach to design verification is testing with flight pyrotechnic devices on actual or closely simulated flight structure. 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 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.

Requests for information, corrections, or additions to this Standard should be directed to Section 352D, Mechanical Systems Engineering and Research Division, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099. Requests for additional copies of this Standard should be sent to NASA Engineering Standards, ED40, MSFC, AL, 35812, (telephone 256-544-2448). This and other NASA standards may be viewed and downloaded, free-of-charge, from our NASA Standards Homepage: http://standards.nasa.gov.

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APPENDICES

PYROSHOCK TEST CRITERIA

1. SCOPE

1.1 Purpose. The objective of this NASA Technical Standard is to provide a consistent methodology for developing 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. 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.

1.2 Applicability. This Standard recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this Standard and its provisions is the responsibility of program/project management and the performing organization. Individual provisions of this Standard may be tailored (i.e., modified or deleted) by contract or specification to meet specific program/project needs and constraints.

1.3 Background

1.3.1 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).

1.3.2 Pyroshock characteristics. Pyroshock is often characterized by its high peak acceleration (up to 300,000 g), high frequency content (up to 1 MHz), and short duration (less than 20 ms), which is 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. Thus, pyroshock verification should be accomplished experimentally, and pyroshock testing is considered essential to mission success.

1.3.3 Potential hardware effects. Many flight hardware failures have been attributed to pyroshock exposure, some resulting in catastrophic mission loss [5]. 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, 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.

1.4 Summary of pyroshock environmental categories. In this Standard, the pyroshock environment has been divided into the following three categories, depending on the shock severity and frequency range: (a) near-field, (b) mid-field, and (c) 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, 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.

1.5 Summary of pyroshock test criteria. Specific pyroshock test requirements are selected based on: (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 maximum expected flight environment as specified in Section 4.2; (e) test margins as discussed in Section 4.3; (f) test specifications described in Section 4.4; and (g) the test method and facility as outlined in Section 4.5.

2. APPLICABLE DOCUMENTS

2.1 General. The applicable documents cited in this Standard are listed in this section for reference purposes only. The technical requirements listed under Requirements in this Standard must be met whether or not the source document is cited.

2.2 Government documents.

2.2.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this Standard to the extent specified herein. Unless otherwise specified, the issuances in effect on the date of invitation for bids or requests for proposal shall apply.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA-STD-7002 “Payload Test Requirements”, July 10, l996.

2.2.2 Reference documents. See Appendix C.

2.3 Order of precedence. Where this Standard is adopted or imposed by contract on a program or project, the technical guidelines of this Standard take precedence, in the case of conflict, over the technical guidelines cited in other referenced documents.

3. ACRONYMS, SYMBOLS AND DEFINITIONS

3.1 Acronyms and symbols used in this standard

%	percent
β	fractional portion
γ	confidence coefficient
d	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/s
i	sample number
in.	inches
k	kilo or 10^3
$k_{n,\beta,\gamma}$	normal tolerance factor
L	tolerance limit
m	meters
M	mega or 10^6
MEFE	maximum expected flight environment
n	(a) natural or new (subscript), (b) total number of samples
PF	protoflight
Q	quality factor
Qual	qualification
r	reference (subscript)
s	(a) second, (b) 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 used in this standard

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.

3.2.2 Pyrotechnic source categories. Pyrotechnic devices may be divided into two general categories: point sources and 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, 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: near-field, mid-field, and 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:

a. The near-field environment is dominated by direct wave propagation from the source, causing peak accelerations in excess of 5000 g and substantial spectral content above 100 kHz. For very intense sources, such as most line sources, the near-field usually includes structural locations within approximately 15 cm (6 in.) of the source (unless there are intervening structural discontinuities). For less intense sources, such as most point sources, the near-field usually includes locations within approximately 3 cm (1 in.) of the source. 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 5000 g and substantial spectral content above 10 kHz. For very intense sources, the mid-field usually includes structural locations between approximately 15 cm and 60 cm (2 ft) of the source (unless there are intervening structural discontinuities). For less intense sources, the mid-field may extend between 3 cm and 15 cm of the source.

c. The far-field environment is dominated by structural resonances, with peak accelerations below 1000 g and most of the spectral content below 10 kHz. The far-field distances occur outside the mid-field.

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 [6]. Temporal moments may also be used to characterize the waveform, including the duration [7]. A typical acceleration time history is shown in Figure 1.

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 [8].

b. One or more of the following spectra may be computed to characterize the frequency content of a transient: Fourier, “energy”, or shock response (SRS) [6,9]. The SRS is the one most commonly used for pyroshock environment and test description. *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 1/6 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 [6,9]. The latter SRS envelopes the previous four and is the one most commonly used for pyroshock testing. A typical maximax SRS is shown in Figure 2. The SRS acceleration is also called the maximum or peak absolute response acceleration.

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

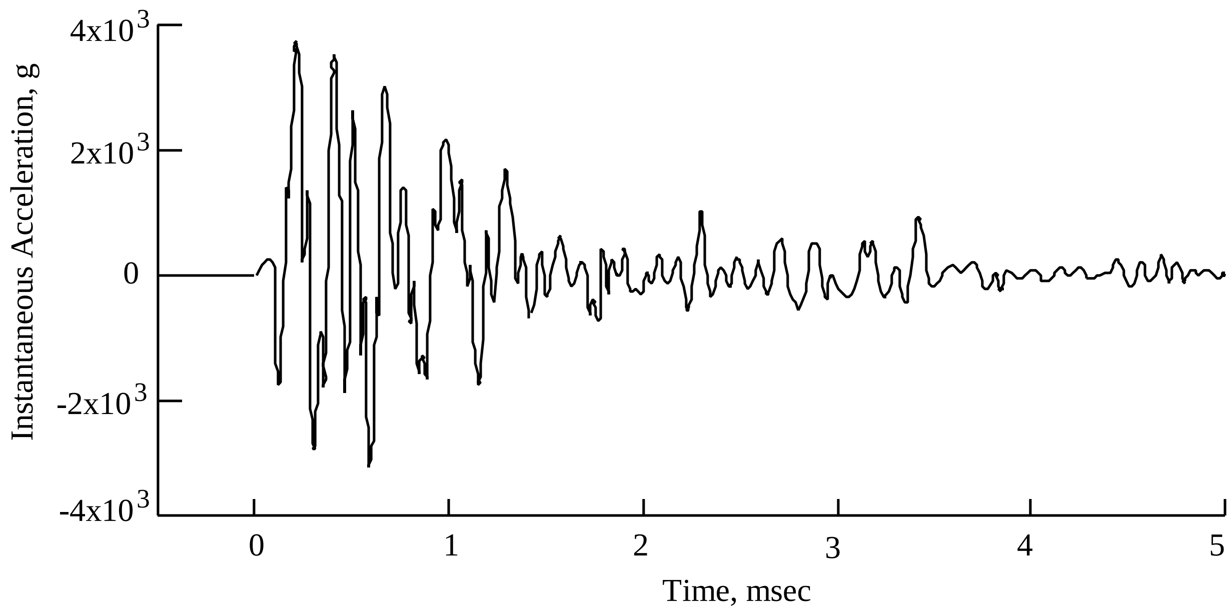

FIGURE 1. Typical Pyroshock Acceleration Time History

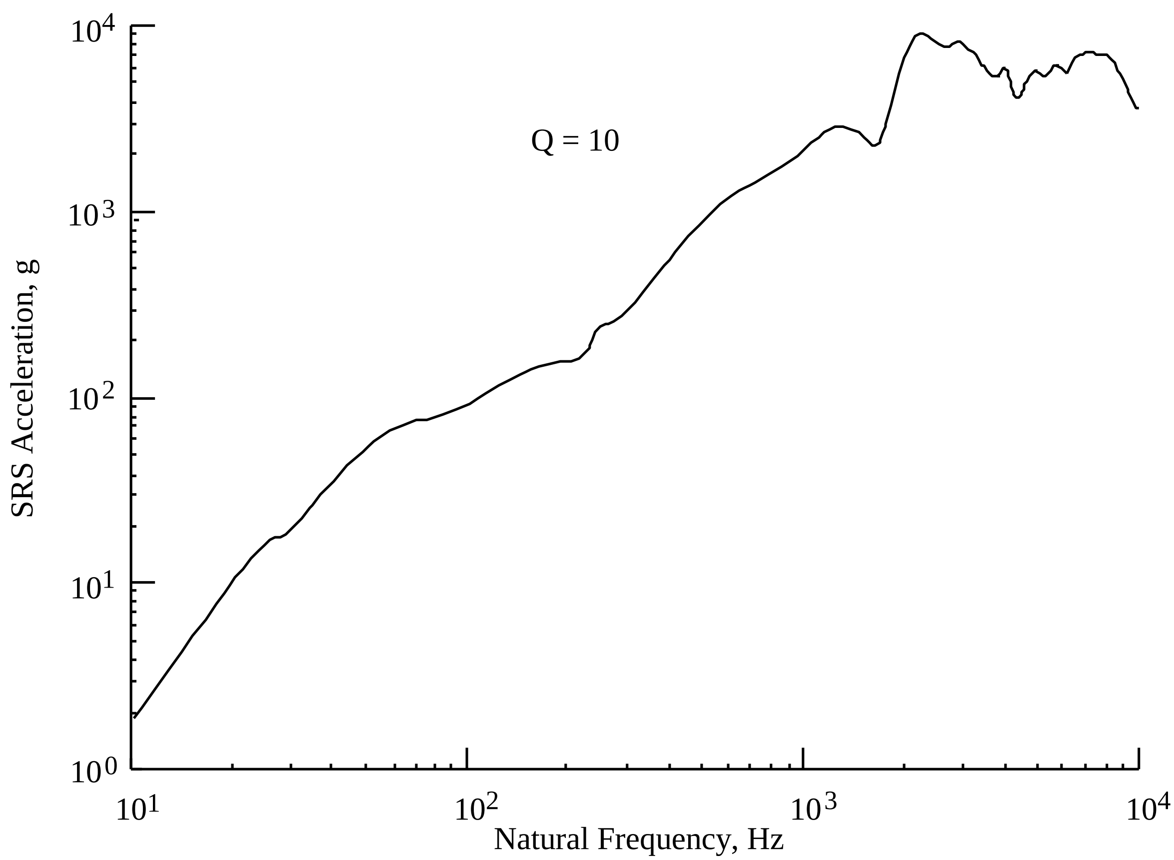

FIGURE 2. Typical Pyroshock Maximax Shock Response Spectrum (SRS)

3.2.5 Environmental test categories. There are four programmatic categories under which pyroshock tests are usually performed:

a. A qualification (Qual) or prototype 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. A flight acceptance (FA) test is performed 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 protoflight (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.

These categories are also used to classify 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. 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

4.1 Pyroshock test rationale. The rationale for assembly-level pyroshock testing is to provide design and/or workmanship verification of the assembly for pyroshock loading prior to the integration of the assembly with the flight system. The rationale for system-level pyroshock testing is generally to (a) provide design and/or workmanship verification of the assembled flight system for pyroshock loading, and (b) verify assembly-level test environments or justify the omission of assembly-level testing. The decision to perform or omit pyroshock testing should be based on (1) the known ruggedness or robustness of the hardware, (2) the relative severity of the pyroshock environment compared to lower frequency dynamic environments, such as random vibration, and (3) 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 (a) 100 Hz for near-field pyroshock, (b) 500 Hz for mid-field pyroshock, and (c) 1 kHz for far-field pyroshock [5]. Small components are more likely to be susceptible to pyroshock failure in all three categories [13], unless they are protected from the high frequency environment, e.g., by resilient mounts or elements. *If there is a serious question about the hardware susceptibility to pyroshock, then pyroshock testing should 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.

4.2 Maximum expected flight environment. Pyrotechnic test criteria should be based upon the maximum expected flight or service environment (MEFE), which may be estimated from (a) a transient analysis, (b) an envelope of measured flight or ground test data, or (c) a statistical analysis of these measured data. The last alternative is preferred when there are three or more measurements. When statistical analysis is selected, it is common to utilize 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. However, other statistical parameters may be used. 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 fail the same test conditions because of hardware strength variability. Thus, pyroshock Qual testing for externally-induced pyroshock environments is usually performed with a magnitude margin added to the MEFE to account for this variability. Furthermore, a fatigue or time-dependent margin is often added. A minimum of 3 dB is recommended to be added to the MEFE uniformly across the spectrum. In cases where the MEFE is obtained from a liberal envelope over the measured data, it is sometimes considered that sufficient margin has already been incorporated into the envelope, so that no additional margin is required.

A minimum of two shock applications is recommended for pyroshock Qual testing. When performed, FA testing for externally-induced shock environments is commonly conducted at MEFE conditions with one shock application per axis. PF testing is generally performed at Qual magnitude 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. For Qual and PF testing for self-induced shocks, multiple firings are usually applied to account for firing-to-firing variability. A minimum of two firings is recommended. 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. The other pyrotechnic devices are usually fired once to verify that they do not generate a more severe shock condition for any potentially susceptible hardware. When performed, only one firing is normally applied for FA testing.

4.4 Test specifications. As noted above, pyroshock tests for self-induced pyroshock environments are usually performed by utilizing flight pyrotechnic devices and flight or flight-like structures. *The best pyroshock simulation is generally achieved using actual pyrotechnic devices and flight structure which incorporates 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.* For system-level firing of pyrotechnic devices 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 must be exercised to avoid the inadvertent firing of a pyrotechnic device in the presence of personnel, especially from electromagnetic sources.

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. In these cases it is essential that the test firings be adequately instrumented to measure responses and that Qual or protoflight pyroshock tests be performed on all potentially susceptible assemblies.

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. Pyroshock tests for externally-induced environments should be specified using the SRS, 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 1 MHz (or more) for near-field environments; 100 kHz (or more) for mid-field environments; and 10 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. The required SRS, within the tolerances of Section 4.8, should be achieved in each of three orthogonal axes. As discussed in Section 3.2.4, a constant quality factor of Q=10 should be utilized.

The pyroshock test waveform or time history should have similar characteristics to that of the flight event, e.g., several frequency-dependent decaying sinusoids occurring simultaneously. The total pyroshock duration should also be similar to that of the flight event, usually less than 10 ms.

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 is 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) a pyrotechnic device [1,10,11]; (b) 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) [11,12]; or (c) a vibration exciter or shaker programmed to generate short duration transient motion [11,13]. 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 must be stressed 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 [12]. 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 variation in the shock from test to test.

There is a variety of custom and commercially-available impact device shock simulators [12]. 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 [12]. 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 100 kHz.

Electrodynamic and electrohydraulic 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 must 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 [6]. 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 [6]). 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 [6]. In recent years, two accelerometer developments have permitted improved pyroshock measurement quality: (a) piezoresistive accelerometers having natural frequencies in excess of 1 MHz and shock limits in excess of 200,000 g, and (b) accelerometers with built-in or attached shock isolators or mechanical filters [6]. Unless care is exercised in their selection, accelerometers located on flexible structures may erroneously generate electrical signals caused by base bending [6].

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 “head room” [6,14]. 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 [6,14]. 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 [6,15,16]. 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 [1,17]. 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 [6].

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 waveform should equal or approximate the measured pyroshock SRS, called the zero period response acceleration [6].

When digital data acquisition and/or analysis are utilized, the digital sampling rate should equal or exceed 10 times the highest SRS natural frequency. Before analog-to-digital conversion is applied to the analog signals, it is important to utilize anti-aliasing filters before the ADC [6]. Other major sources of instrumentation errors should also be avoided [6]. 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 [17]. 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 [6], Sections A.3.5 - A.3.6). Even the SRS computational algorithm may cause an appreciable effect on the resulting spectrum [18,19]. The Smallwood algorithm has been recommended to reduce algorithm-induced variability [20].

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, various tolerances have historically been utilized. The tolerances most commonly used in current aerospace practice are specified for the maximax SRS:

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

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

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.

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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: (a) analytical models, (b) direct measurements, and (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 [2,21,22]. 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 [23-26]. 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 [6]. 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: (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; and (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: (a) the procedure allows the determination of the pyroshock environment due only to a limited number of pyrotechnic devices; and (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 alter the spacecraft structure, pyroshock measurements on prototypes are usually made after all other tests are complete. The advantages of a prototype test are: (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; and (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: (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; and (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., [3,4]. 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: (a) scaling for the total energy released by the pyrotechnic device, and (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 [3,4,27], 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 to the new vehicle by [27]

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

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 [3,4,27]. One set of scaling curves for typical pyroshocks propagating through various types of structure, as developed in [3], is summarized in Figure A.1. Note the results in Figure A.1 apply to the peak value of the pyroshock response.

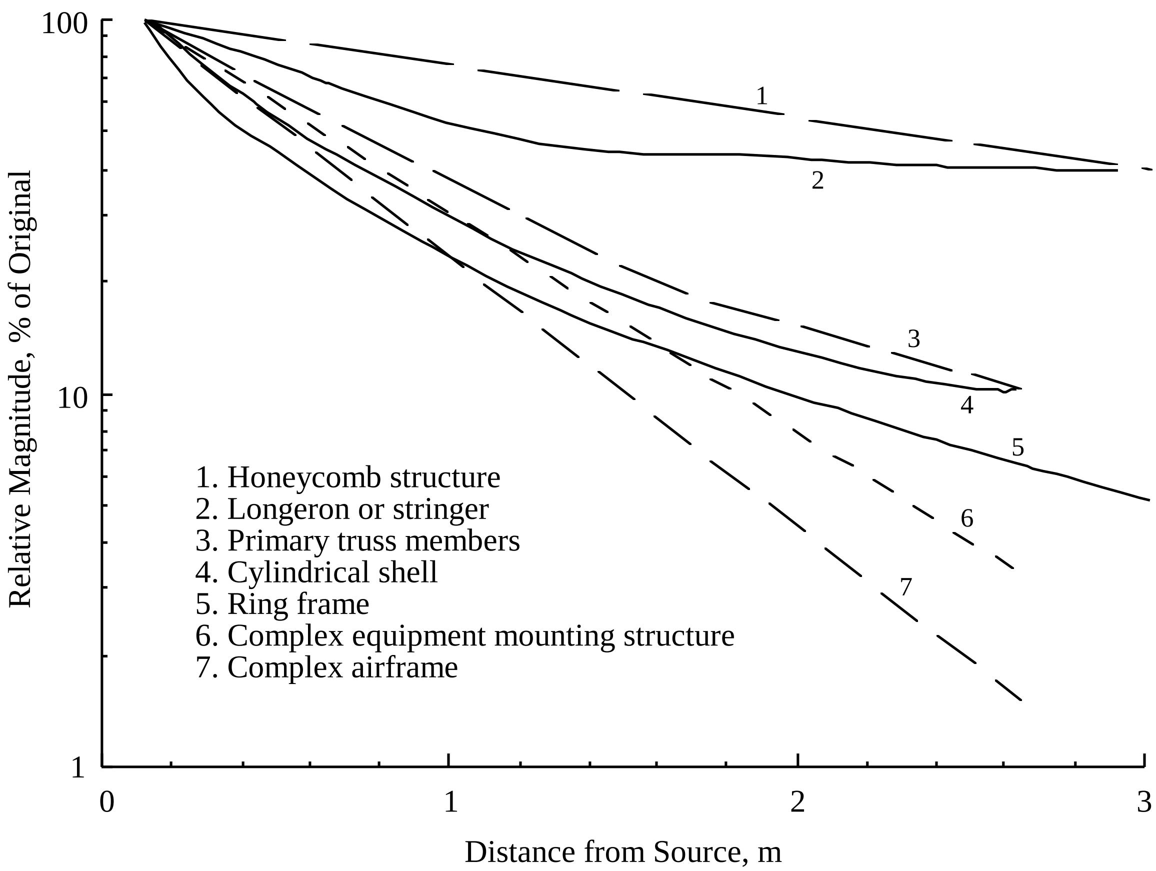

FIGURE A-1. Peak Pyroshock Response versus Distance from Pyrotechnic Source

Another scaling relationship developed in [27] for the shock response spectrum produced by point sources on complex structures is given by

$$\mathrm{SRS}(D_2) = \mathrm{SRS}(D_1)\exp\left\{\left[-8\times10^{-4} f_n^{\left(2.4 f_n^{-0.105}\right)}\right]\left[D_2 - D_1\right]\right\} \qquad \text{(A.2)}$$

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 SRS(D_1) and 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 $dD = D_2 - D_1$ are shown in Figure A.2.

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 A.1 and A.2 [28].

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, [3] suggests 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, [27] suggests a 50 percent reduction for a major discontinuity, and 30 percent per normal joint up to a maximum of three joints. Other joint attenuation data that may be available from prior experience (e.g., [4,27]) should be also be considered, as applicable.

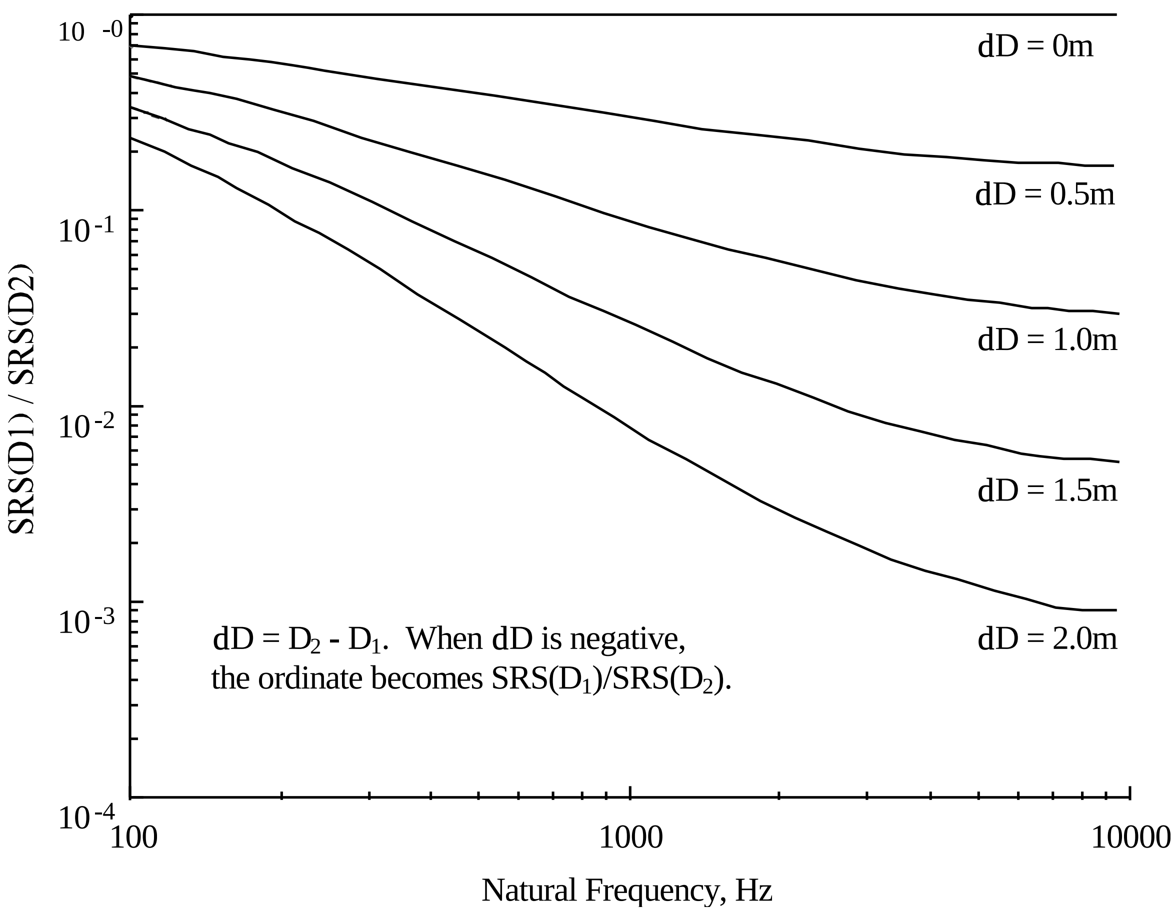

FIGURE A-2. Correction of Shock Response Spectrum for Distance from Pyrotechnic Source

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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 two steps, (a) the division of the predictions for a specific pyrotechnic event into groups with similar SRS values, referred to as "zones", and (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 [29]. 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 [30]. 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, (100β)/(100γ), e.g., the P95/50 normal tolerance limit represents β = 0.95 and γ = 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 [6,31]. Hence, by simply making the logarithmic transformation

$$y = \log_{10} x \qquad \text{(B.1)}$$

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 $\bar{y}$ 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 $\beta = 0.95$ and $\gamma = 0.50$ is presented in Table B.1, which is taken directly from [30]. 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 two straight lines segments, as found in [11, 12].

TABLE B.I. 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

REFERENCE DOCUMENTS

C.1 Government documents, drawings and publications. The following documents form a part of this standard to the extent specified herein. Unless otherwise specified, the issuances in effect on the date of invitation for bids or requests for proposal shall apply.

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C.2 Non-Government publications. The following documents form a part of this Standard to the extent specified herein. Unless otherwise specified, the issuances in effect on the date of invitation for bids or requests for proposal shall apply.

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