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# White Paper on Factors of Safety

*Ivatury Raju/NESC and John Stadler/NESC*
*Langley Research Center, Hampton, Virginia*

*Julie Kramer-White/NESC*
*Johnson Space Center, Houston, Texas*

*Robert Piascik/NESC*
*Langley Research Center, Hampton, Virginia*

October 2012

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*Langley Research Center, Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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**Revision History**

Revision 1 (Oct. 2012) - Table 3.2 has been revised and included as Appendix C.



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NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

## Signature Page

Original signature on file
Ivatury Raju, Lead, NESC-LaRC
NDE - Structures

Original signature on file
John Stadler, NESC-LaRC
SEO – Systems Engineer

Original signature on file
Julie Kramer-White, NESC-JSC
NDE – Mechanical Analysis

Original signature on file
Robert Piascik, NESC-LaRC
NDE - Materials

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## 1. EXECUTIVE SUMMARY

Following the Columbia Accident Investigation Board (CAIB) Report, the "Diaz Team" identified CAIB Report elements with Agency-wide applicability. The "Diaz Report", *A Renewed Commitment To Excellence*, generated an action to "Review current policies and waivers on safety factors". This white paper addresses this action.

Four different projects from four different centers were audited on their definition, requirements, and use of structural ultimate Factor of Safety ($FOS_{ult}$): Orbiter managed at JSC, External Tank managed at MSFC, X-43 managed at DFRC, and the Swift spacecraft managed at GSFC.

The projects were asked to provide the document that defines their $FOS_{ult}$ requirements, provide the $FOS_{ult}$ requirement, provide the project's definition of the $FOS_{ult}$, and provide a list of any waivers to the $FOS_{ult}$ requirement.

All of the projects audited utilize NASA-STD-5001 for the overall structure $FOS_{ult}$ requirements but ultimately customized the NASA-STD-5001 requirement(s) into their own internal requirements document.

The vast majority of the projects met NASA-STD-5001 structural $FOS_{ult}$ value of 1.4. As expected, there were exceptions when a waiver was granted or the requirement relaxed for a particular piece of hardware. Although a technical justification was provided to the waiver/relaxation, the audit found the technical justification was necessary, but not sufficient.

The audit has made the following five recommendations. These are discussed in more detail in Section 6 of this paper.

1. **$FOS_{ult}$ for no-test hardware**: Perform study to determine if higher $FOS_{ult}$ values are required for no-test hardware and update NASA-STD-5001 to include specific guidance and suggested no-test FOS requirements.

2. **Requirement Relaxation:** Reduction of the standard $FOS_{ult}$ value should be documented via a waiver or deviation as opposed to a relaxation of the requirement.

3. **$FOS_{ult}$ Waivers should not be used as a Precedent:** For reusable or recurring flight hardware, a waiver should be considered a one time exception and not a precedent.

4. **Maintaining $FOS_{ult}$ Over the Life of a Program:** Due to aging effects, the Margin of Safety ($MOS_{ult}$) and $FOS_{ult}$ should be periodically reevaluated.

5. **Probabilistic Approaches (PA):** Conduct a study to determine if Probabilistic Approaches can be used as an alternate method to traditional FOS methods. PA may exhibit excellent promise in reducing the FOS requirements while maintaining the overall reliability of the system.

## 2. INTRODUCTION

The CAIB provided the following Observation:

O10.10-1 NASA should reinstate a safety factor of 1.4 for the Attachment Rings, which invalidates the use of ring serial numbers 16 and 15 in their present state, and replace all deficient material in the Attachment Rings.

**Background**

The External Tank Attach (ETA) rings are located on the Solid Rocket Boosters (SRBs) on the forward end of the aft motor segment (Figure 2-1). The rings provide the aft attach points for the SRBs to the External Tank (ET). Tensile tests of ETA ring web material found the ETA ring material strengths were lower than the design requirement. The ring material was from a previously flown and subsequently scrapped ETA ring which is representative of current flight inventory material.

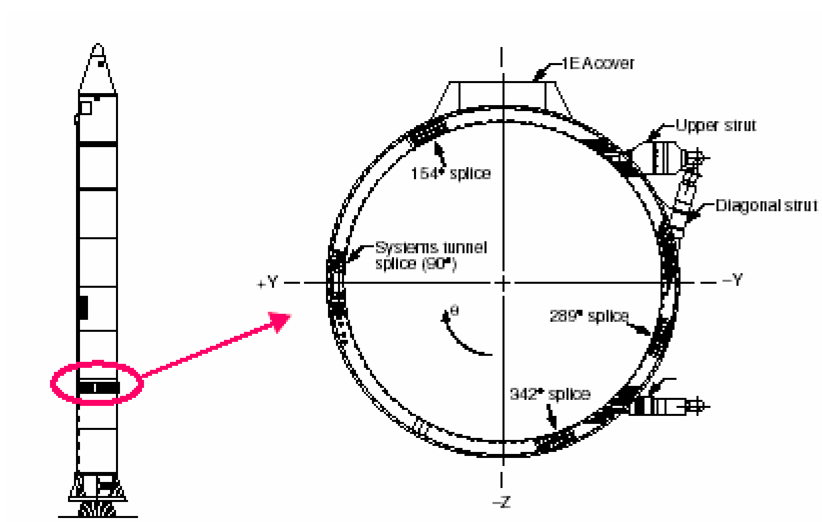


Figure 2-1. SRB External Tank Attach Rings

Following the CAIB Report, the NASA Administrator assigned an Executive Team to identify CAIB Report elements with Agency-wide applicability. This team became known as the “Diaz Team” and its Report, *A Renewed Commitment To Excellence*, as the “Diaz Report”.

Based on the above CAIB observation, the Diaz Report found “design and safety factors have been developed by many engineering and manufacturing organizations with a broad base of underlying test and supporting data" and the Office of Chief Engineer assigned the following specific action to NESC – Action Item 16:

16) Review current policies and waivers on safety factors.

   a. Conduct an audit of no less than three programs. Determine if the programs are using a 1.4 safety factor, and what waivers have been granted.
   b. Compile the results and develop a recommendation.
   c. If required, develop or rewrite a policy for minimum safety factors, and associated waivers.

The purpose of this white paper is to document the response(s) to the above action item. The paper is organized in the following order.

- An overview is presented of the FOS.
- Review of the structural FOS standards used at several of the NASA Field Centers.
- Survey of $FOS_{ult}$ used by four programs at various centers and the results of the audit of these $FOS_{ult}$ are presented.
- Discussion of waivers used by various programs and followed by the recommendations.

This report utilizes the definitions for various terms presented in Section 3 of the NASA-STD-5001 [1]. Relevant definitions used in this document are presented in Appendix A.

# 3. FACTORS OF SAFETY (FOS)

## 3.1. General

To account for uncertainties and unknowns, including material variations, analysis uncertainties, etc., a structural member must be designed to carry a load considerably larger than the maximum expected applied load. To determine the appropriate design load, the maximum expected applied load is multiplied by a FOS. In the 1930's there was ambiguity among the definitions used for design load, expected load and applied loads. Therefore, the U.S. Army Air Corps established the following definitions summarized in Table 3-1 which are used today in the Aerospace industry.

**Table 3-1. Terminology Definitions**

| Term | Definition |
|---|---|
| Limit Load | Maximum expected load on the structure. |
| Ultimate Load[1] | Product of the Limit Load times the Ultimate Factor of Safety ($FOS_{ult}$). This is the load for which a structure is designed for ultimate strength and must be less than the Allowable Ultimate Load. |
| Yield Load | Product of the Limit Load times the Yield Factor of Safety ($FOS_{yield}$). This is a load for which a structure is designed for yield strength and must be less than the Allowable Yield Load. |
| Allowable Ultimate Load | The highest load that will not cause material failure. |
| Allowable Yield Load | The highest load that will not cause material plastic deformation. |
| Note 1) Ultimate Load is also often referred to as "Ultimate Design Load" or "Design Ultimate Load". | |

Therefore the Factor of Safety is defined as:

$$FOS_{ult} = \frac{\text{Ultimate Load}}{\text{Limit Load}}$$

$$FOS_{yield} = \frac{\text{Yield Load}}{\text{Limit Load}}$$

The Aerospace industry also uses an additional term called the Margin of Safety (MOS). The MOS relates the design load to the allowable load.

$$\begin{aligned} MOS_{ult} &= \frac{\text{Allowable Ultimate Load}}{\text{Ultimate Load}} - 1 \\ &= \frac{\text{Allowable Ultimate Load}}{\text{Limit Load} \cdot FOS_{ult}} - 1 \end{aligned}$$

and

$$\begin{aligned} MOS_{yield} &= \frac{\text{Allowable Yield Load}}{\text{Yield Load}} - 1 \\ &= \frac{\text{Allowable Yield Load}}{\text{Limit Load} \cdot FOS_{yield}} - 1 \end{aligned}$$

When the $MOS_{ult}$ equals zero, the Allowable Ultimate Load, or capability, equals Ultimate Load, the load for which the structure was designed.

Figure 3-1 schematically presents the loads defined above and the relationship between $FOS_{ult}$ and $MOS_{ult}$. The load is plotted against the stress of a linear elastic structure. This is an idealized figure for illustration purposes only.

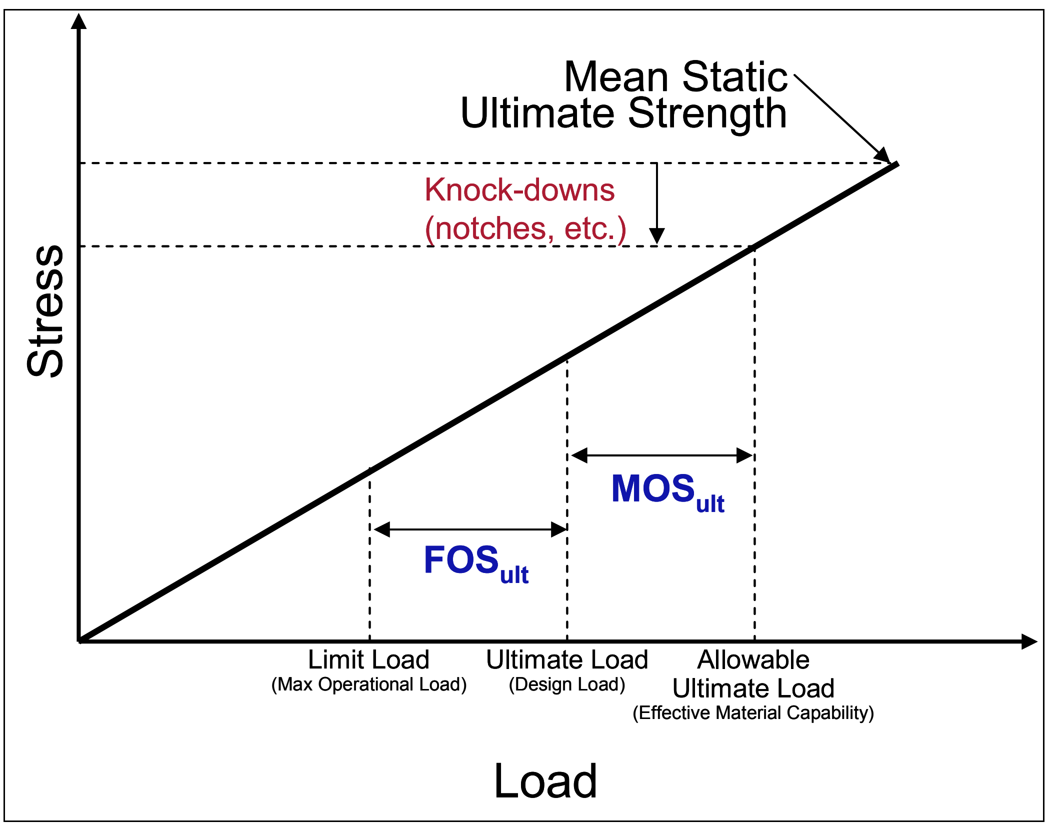


Figure 3-1. Graphical Illustration of Relationship between FOS and MOS.

### 3.1.1. Alternate Definitions

Some additional discussion on the definition of FOS and MOS is pertinent here. The definitions above are used widely throughout the Aerospace industry including NASA. Recall that the Ultimate Load is the product of the Limit Load and $FOS_{ult}$, and according to this definition the Ultimate Load has no relationship to the material Allowable Ultimate Load. However, the $MOS_{ult}$ relates the Ultimate Load to the Allowable Ultimate Load.

In numerous non-aerospace fields, as well as many classical mechanical engineering text books, the concept of a separate design load is not used and the FOS is simply defined as:

$$FOS_{ult} = \frac{\text{Allowable Ultimate Load}}{\text{Limit Load}}$$

and MOS is defined as:

$$MOS_{ult} = FOS_{ult} - 1 .$$

Additionally, since the relationship between load and stress is often linear, many engineering texts will define the FOS and MOS with respect to stress as opposed to loads.

The above definitions are different than those used throughout NASA. Throughout this white paper, therefore, the definitions in Section 3.1 apply.

### 3.2. Basis of Factor of Safety

The FOS utilized in aerospace design is intended to cover various uncertainties in the way the structure is analyzed. The magnitude of the factor is dependent upon how accurately the structure is understood and modeled, material property understanding, and manufacturing control processes. The factor is based on engineering judgment and experience.

The determination of this factor must consider the following:

- Types of loads
  - Static or dynamic
  - Cyclic loading
- Processing and fabrication defects (variability on workmanship quality)
- Variations in material properties
- Accuracy and methods of analysis
  - Limitations of modeling methods/techniques (e.g. two-dimensional, shell, three-dimensional, etc.)
  - Limitations of analysis methods (e.g.. finite element method, boundary element method, etc.)
  - Inadequate knowledge of factors such as boundary conditions, residual stresses, etc.
  - Limitation of analysis types (e.g. linear elastic, elastic-plastic, dynamics, etc.)
- Failure mode criticality
  - Catastrophic
  - Non-catastrophic
  - Redundancy
- Levels of test verification
  - Test vs. No test
  - Component vs. System
- Manned vs. Unmanned Mission

The FOS is applicable for the life of the system and, therefore, must address any material property degradation during service.

The FOS is not designed to account for uncertainty of external loads, major variation in material properties (poor material manufacturing process control, material defects such as flaws, cracks, voids, etc.), or poor/limited understanding of failure modes.

In 1932 there was evidence that components of successfully designed airplanes did not yield, that is, permanently deform. Since the common structural material at that time was 17ST aluminum alloy having an ultimate-to-yield stress ratio of 1.5, the arbitrary 1.5 safety factor at ultimate was universally accepted. Since this factor is determined from historical experience rather than physics-based methodologies, there is a tendency to challenge its value and application.

### 3.3. $FOS_{ult}$ for Airframes

The $FOS_{ult}$ for airframes is defined as in Section 3.1, the ratio of ultimate load to the limit load. The limit load is the highest load experienced by the structural component in the life of the aircraft fleet. The $FOS_{ult}$ conventionally used for commercial transport aircraft airframes remains at 1.5.

### 3.4. $FOS_{ult}$ for Aerospace Structures

Based on improved aluminum alloys, and involving historically-driven programmatic requirements for optimized performance, a 1.4 design ultimate safety factor is now the official NASA standard as defined in NASA-STD-5001 for metallic structures (Protoflight Approach [1]). This commonly utilized aerospace structural FOS is considered applicable for a system with well characterized materials, well understood load paths, and manufactured to aerospace standard processes. Note that for non-metallic materials, such as composites, a higher ultimate factor of safety is used (see NASA-STD-5001).

The NASA–STD-5001 [1] establishes recommended practice of standard structural design and test factors for space flight hardware development and verification. In addition, NASA-STD-5005 [2] provides design criteria for ground support equipment while STD–5003 [3] and STD-5007 [4] provide fracture control requirements for payloads using the space shuttle and manned space flight systems, respectively.

A historical perspective of the design FOS used throughout major NASA missions is summarized in Table 3.2.

## Table 3.2. Historical Design Factors for NASA Space Vehicles

*(Data summarized in this table was provided by NASA JSC)*

| HISTORIC DESIGN FACTORS FOR SPACE VEHICLES<br>Component | Factor | Apollo (NASA-MSC) | Gemini (NASA-MSC) | Mercury (NASA-MSC) | MOL (USAF) | DYNA SOAR (USAF) | Skylab S-IVB (NASA-MSFC) | Shuttle | Space Hab | ISSA SSP 30559 | S-IVB (NASA-MSFC) | S-II (NASA-JSFC) | S-I (NASA-MSFC) | Manned-General NASA-MSC | Manned-General NASA-MSFC | Manned-General AFSC-DH 3-2[6] | Airlock (MDAC - St. Louis) | Lunar Orbiter (Boeing) | Thor/Delta Thor/Agena (MDAC - Santa Monica) | Unmanned Spacecraft (Lockheed MSC) | Agena (Lockheed MSC) | Polaris (Lockheed MSC) | Scout (LTV Aerospace) | Atlas (GD/C) | Pioneer | Viking (MMC - JPL) | Titan III-C (MMC) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| General Structure | Yield | 1.1 | 1.1 | 1.1 | 1.0 | | 1.1 | - | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.15 | 1.0 | 1.0 | 1.0 | 1.0 | 1.15 | 1.0 | 1.0 | 1.0 | 1.0 |
| | Ultimate | 1.5 | 1.36 | 1.5 | 1.4 | 1.5 | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.36 | 1.5 | 1.25 | 1.25 | 1.25 | 1.25 | 1.5 | 1.25 | 1.5 | 1.25 | 1.25 |
| Tanks-Liquid Propellant and Other Fluids-Cryogenics | Yield | 1.33 | - | - | 1 | 1.5 | 1.1 | | | | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | | | | | | | | | | | | 1.0 |
| | Proof | 1.33 | 1.5 | 1.5 | 1.5 | 1.5 | 1.05 | | | | 1.1 | 1.05 | 1.1 | 1.1 | 1.05 | 1.5 | | | 1.05 | 1.67 | 1.1 | | | | | | 1.0 |
| | Ultimate | 1.5 | 2.0 | 2.0 | 2.0 | 1.33 x 1.5 | 1.4 | | | | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.33 x 1.5 | | | 1.33 | 2.22 | 1.25 | | | 1.25 | | | 1.25 |
| Propellant Lines | Yield | - | - | - | - | - | - | | | | | | | | | 1 | | | | | | | | | | | |
| | Proof | - | - | - | - | - | - | | | | | | | | | 1.5 | | | | | | | 1.5 | | | | |
| | Ultimate | - | - | - | - | - | - | | | | | | | | | 1.88 | | 1.65 | | | | | 2.5 | | | | |
| Vessels (High Pres Bottle) Vent Lines Plumbing, etc. | Yield | 1.33 | 1.0 | 1.0 | 1.0 | - | 1.1 | | | | 1.1 | 1.15 | 1.15 | 1.33 | 1.1 | | 1.0 | 1.5 | | | | | | 1.0 | | 2.25 | |
| | Proof | 1.33 | 1.67 | 1.7 | 1.5 | - | 1.1 | | | | 1.1 | 1.05 | 1.05 | 1.33 | 1.05 | | 1.67 | 2.0 | 1.33 | | | | | 1.67 | 1.66 | 2.0 | |
| | Ultimate | 1.5 | 2.22 | 2.2 | 2.0 | - | 4.0 | | | | 4.0 | 1.4 | 1.4 | 2.0 | 1.4 | | 2.22 | | 1.5 | | | | | 2.0 | 2.0 | 4.0 | |
| Pressurized Structure-Cabins, Airlocks, Ducts, etc. | Yield | 1.0 | 1.0 | 1.3 | 1.0 | 1.0 | - | - | 1.65 | 1.7 | | | | | | 1.1 | 1.0 | | | | | | | | | | |
| | Proof | NA | 1.33 | - | 1.33 | 1.2 | - | 1.1 | 1.5 | 1.5 | | | | | | | 1.36 | | | | | | | | | | |
| | Ultimate | 1.5 | 2.0 | 2.0 | 2.0 | 1.5 | - | 1.5 | 2.0 | 2.0 | | | | | | 1.4 | 2.0 | | | | | | | | | | |
| Hydraulic and Pneumatic Sys. (Incl. Lines, Fitting, Tubing) | Yield | - | 1.0 | 1.0 | 1.0 | | 1.1 | | | | 1.1 | | | | | 1.0 | 1.0 | 2.0 | | | | | 1.5 | | | 2.25 | 2.0 |
| | Proof | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | | | | 2.0 | 2.0 | | | | 2.0 | 2.0 | 2.0 | 2.5 | 2.0 | 1.5 | | 1.5 | | | 2.0 | 2.0 |
| | Ultimate | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | | | | 4.0 | 4.0 | | | | 4.0 | 4.0 | 4.0 | 5.0 | 4.0 | 3.0 | | 2.5 | | | 4.0 | 4.0 |
| Nonflight: Dangerous To Personnel | Yield | | | | 1.0 | | | | | | | | | | | 1.0 | | | 1.5 | | | | | | | 1.6 | |
| | Ultimate | | | | 1.5 | | | | | | | | | | | 1.5 | | | 4.0 | | | | | | | 2.0 | |
| Nonflight: Not Danger-ous To Personnel | Yield | | | | 1.0 | | | | | | | | | | | 1.0 | | | 1.0 | 1.15 | | 1.15 | | | | | 1.0 |
| | Ultimate | | | | 1.25 | | | | | | | | | | | 1.25 | | | 1.33 | 1.50 | | 1.50 | | | | | 1.25 |
| Pneumatic and Hydraulic System Components Heat Exchangers (Including Cold Panels). Quick Disconnect, Blowers, ValvesPressure Switches, Regulators | Yield | | 1.0 | 1.0 | 1.0 | | | | | | | | | | | | 1.0 | | | | | | | | | | 1.0 |
| | Proof | 1.33 | 1.5 | 1.5 | 1.5 | 1.5 | | | | | | | | | | | 1.5 | | | 1.5 | | | | | | | 1.5 |
| | Ultimate | 1.5 | 2.5 | 2.5 | 2.0 | 2.5 | | | | | | | | | | | 2.5 | | | 2.5 | | | | | | | 2.5 |

# 4. CURRENT FACTOR OF SAFETY STANDARDS

## 4.1. NASA FOS Standards

Many of the field centers developed customized standards to address applications not included in NASA-STD-5001, as presented in Table 4-1.

**Table 4-1. Structural FOS Standards used at the NASA Field Centers**

| NASA Field Center | Commonly used Standards[1] |
|---|---|
| Dryden Flight Center | DHB-R-001 *Dryden Flight Research Center Hand Book For Structural Design, Proof Test, and Flight Test Envelope Guidelines* [5] |
| Glenn Research Center | NASA-STD-5001 *Structural Design and Test Factors of Safety for Spaceflight Hardware* [1] |
| Goddard Space Flight Center | GSFC-GEVS-SE *General Environmental Verification Specification* [6] |
| Johnson Space Center<br>Space Shuttle Program (SSP)<br>Space Shuttle Payloads<br>International Space Station | NSTS 07700 Vol X *Space Shuttle Flight and Ground System Specification, and the Shuttle Interface Control Documents (ICD's)* [7]<br>NSTS 1700.7B *Safety and Policy Requirements for Payload using STS*[8]<br>NSTS 14046D Payload Verification Requirements<br>SSP *30559 Structural Design and Verification Requirements* |
| Langley Research Center | NASA-STD-5001 *Structural Design and Test Factors of Safety for Spaceflight Hardware* [1] |
| Marshall Space Flight Center<br>Space Shuttle Elements<br>General | NASA-STD-5001 *Structural Design and Test Factors of Safety for Spaceflight Hardware* [1]<br>MSFC-HDBK-505A *Structural Strength Design and Verification Requirements* [9]<br>NSTS 07700 Vol X *Flight and Ground System Specification - Book 1, Requirements* [7]<br>ED22-OWI-001 *MSFC Organizational Work Instruction, Strength Analysis* [10] |
| Stennis Space Center | ASME Boiler Standards |

Note:
1) This Table is not intended to be an exhaustive listing of all of the Standards used at the NASA Field centers, but as an indication of the various documents used.

### 4.2. Non-NASA Standards

The Federal Aviation Administration (FAA) requires an aircraft structural $FOS_{ult}$ of 1.5. Similarly, the Department of Defense (DoD) requires an $FOS_{ult}$ of 1.5 for aircraft and 1.4 for aerospace structures [11]. Table 4-2 below lists $FOS_{ult}$ and standards used by non-NASA organizations.

**Table 4-2. FOS Standards used by non-NASA Organizations**

| Organization | Standard | $FOS_{ult}$ |
|---|---|---|
| FAA | | |
| • Transport Aircraft | Federal Aviation Regulation Part 25 Sec 25.303 | 1.5 |
| • Normal, Utility, Acrobatic, Commuter Aircraft | Federal Aviation Regulation Part 23 Sec 23.303 | 1.5 |
| DoD | | |
| • Aircraft Structures | MIL-A-8860B | 1.5 |
| • Aluminum Aerospace Structures | MIL-HDBK-340A/ MIL-HDBK-343 | 1.4 |

## 5. PROJECT $FOS_{ult}$ AUDIT

Five Projects were selected for the survey: ***Orbiter, External Tank, X-43 ,other Space Shuttle Program Elements,*** and ***Swift Spacecraft***, located at JSC, MSFC, DRFC, and GSFC, respectively. From each of the centers, an engineer was chosen to research the $FOS_{ult}$ and waivers from the project. The engineers acquired the answers to the following questions:

1. What documents does the program use to define the requirements for structural $FOS_{ult}$?
2. What is the requirement for structural $FOS_{ult}$?
3. How is this factor defined?
4. Does the program have any waivers or deviations from this requirement?
5. Where are these deviations or waivers documented?
6. Provide a list of the current waivers to structural $FOS_{ult}$.

Table 5-1 summarizes the center, audited program/project, and the engineer responsible for the research and audit.

**Table 5-1. Summary of Center, Project, and Audit Engineer**

| Center | Project | Engineer |
|---|---|---|
| JSC | Orbiter | J. Kramer-White |
| MSFC | External Tank | J. Neeley |
| JSC | Other Shuttle Program Elements | J. Kramer-White |
| DRFC | X-43 | M. Kehoe |
| GSFC | Swift spacecraft | A. Posey |

After the initial research was concluded, the engineers were asked to audit the programs $FOS_{ult}$ and the waivers. The audit involved an independent review of the program documentation and determination of reported $FOS_{ult}$ and review of the initial and final waivers and deviations.

The following sections describe the results of the research and the audit of each of the programs.

### 5.1. Orbiter (J. Kramer-White, JSC)

#### 5.1.1. Document(s) for structural $FOS_{ult}$

The Orbiter structural $FOS_{ult}$ is defined in NSTS 07700, Volume X, *Flight and Ground System Specification - Book 1, Requirements* [7]. The $FOS_{ult}$ requirements are detailed in Section 3.2.2.1.5, *Structure*. Section 3.2.2.1.5 is reproduced in Figure 5-1, a through c.

#### 5.1.2. Requirements for structural $FOS_{ult}$

Ultimate FOSs are listed in NSTS 07700, Volume X, Book 1, Table 3.2.2.1.5.2, *Ultimate Factors of Safety*, which is reproduced in Figure 5-2, a through c. There are no requirements on $FOS_{yield}$.

In general the structure $FOS_{ult}$ must be greater than or equal to 1.4, with more specific requirements for glass, pressurized compartments, pressure vessels, pressurized lines, and landing gear.

### 5.1.3. $FOS_{ult}$ definition

See relevant definitions in NSTS 07700 Volume X, Book1, Section 3.2.2.1.5.1 Definitions [7]. The $FOS_{ult}$ is defined as:

$$FOS_{ult} = \text{Ultimate load/Limit Load}$$

### 5.1.4. Waivers or deviations from this requirement

There are no structural $FOS_{ult}$ waivers for the space shuttle orbiter. This is because the program actively utilizes one of two methods, Modification or Performance Placarding, to avoid a $FOS_{ult}$ lower than the requirements. These methods are briefly discussed below.

**Modification:** When increased systems performance from the NSTS is required, evaluation of the primary structure of the orbiter is conducted. Affected areas are identified and analyzed in detail. On occasion additional capability may be obtained through increased modeling fidelity and/or by decreasing the analytical conservatism. If the performance increase is large, or the ascent trajectory changes are significant, major vehicle modifications may be required. For example, certification of the orbiter for the 6.0 loads cycle required significant modification of the wing root structure; specifically, the addition of several doublers at the spar root to accommodate increased wing loads. Therefore, vehicles could not fly the 6.0 loads trajectories until they had completed the modification program.

**Placarding:** Placarding limits external environments to ensure the $FOS_{ult}$ requirements are met. Vehicle ascent performance placarding may be utilized until such time as the required modifications can be accomplished, or, if the performance penalty is not significant, placarding may be used in lieu of modifications. For example, when a negative margin issue surfaced on Columbia's vertical tail in 1999, the ascent trajectory was modified to preclude reaching critical load. This trajectory modification had a small, negative effect on launch probability and enabled additional flight data to be gathered. The additional flight data allowed a better definition of the loads which ultimately led to removal of the placard.

### 5.1.5. Waivers or deviations documentation

There are no waivers or deviations for the orbiter project.

### 5.1.6. List of current waivers to structural $FOS_{ult}$

There are no waivers or deviations for the orbiter project.

#### 3.2.2.1.5 Structure

The Shuttle Vehicle structure, including pressure vessels and mechanical systems, shall have adequate strength and stiffness, at the design temperature, to withstand limit loads and pressures without loss of operational capability for the life of the vehicle and to withstand ultimate loads and pressures at design temperature without failure. The structure shall not be designed to withstand loads, pressures, or temperatures arising from malfunctions that prevent a successful abort. Major structural elements shall not be designed by non-flight conditions, i.e., conditions other than prelaunch (vehicle mating) through landing except for SRB water recovery. Structure and pressure vessels shall be designed to withstand the effect of a failure of a MPS oxygen or hydrogen ullage pressure flow control valve during nominal ascent. An intact abort combined with the failure of an MPS oxygen or hydrogen ullage pressure flow control valve is not a design requirement for primary structure and pressure vessels.

#### 3.2.2.1.5.1 Definitions

For the purpose of interpretation of this section, the following definitions will apply:

a. Limit Load - The maximum load expected on the structure during mission operation including intact abort.

b. Ultimate Factor of Safety - The factor by which the limit load is multiplied to obtain the ultimate load.

c. Ultimate Load - The product of the limit load multiplied by the ultimate factor of safety.

d. Allowable Load - The maximum load which the structure can withstand without rupture or collapse.

e. Maximum Operating Pressure - The maximum pressure applied to the pressure vessel by the pressurizing system with the pressure regulators and relief valves at their upper limit, with the maximum regulator fluid flow rate, and including the effects of system environment such as vehicle acceleration and pressure transients.

f. Proof Pressure - The pressure to which production pressure vessels are subjected to fulfill the acceptance requirements of the customer, in order to give evidence of satisfactory workmanship and material quality. Proof pressure is the product of maximum operating pressure times the proof factor.

g. Margin of Safety - The ratio of allowable load to ultimate load minus one.

h. Safe-life - A design criteria under which failure will not occur because of undetected flaws or damage during the specified service life of the vehicle; also, the period of time for which the integrity of the structure can be ensured in the expected operating environments.

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Figure 5-1(a). NSTS 07700 Volume X Book 1 Section 3.2.2.1.5

#### 3.2.2.1.5.2 Ultimate Factors of Safety

The ultimate factors of safety given in Table 3.2.2.1.5.2 shall be used for the Shuttle Vehicle structure. The following specific conditions are allowed:

a. The ultimate factors of safety for $LO_2$ tank buckling shall not be less than 1.25 prior to initiation of prepressurization.

b. A safety factor of 1.491 for Power Reactant Storage Assembly is acceptable for Power Reactant Supply and Distribution (PRSD) tank unit-part No. MC282-0063-0100 S/N SX T0010.

c. The ultimate factor of safety for the SSME spark igniter casings shall not be less than 1.25.

d. The ultimate factors of safety for the following SSME pressurized lines and fittings of less than 1.5 inch diameter shall be greater than or equal to 1.5:

| Part Number | Description |
|---|---|
| RS007049 | Rigid Oxidizer Tank Pressurant Duct |
| RS007083 | Heat Exchanger Inlet Line |
| RS007186 | Oxidizer Preburner, Aerodynamic Sensitive Item (ASI) Oxidizer Line |
| RS007187 | Fuel Preburner, ASI Oxidizer Line |
| RS007363 | Tap B06A-To-Transducer Line |
| R0019585 | Fuel System Drying Purge Line |
| R0011053 | Fuel Preburner, ASI Oxidizer Inlet Line |
| RS009525 | Fuel Preburner, ASI Fuel Inlet Tube |
| R0011052 | Oxidizer Preburner, ASI Oxidizer Inlet Tube |
| RS009524 | Oxidizer Preburner, ASI Fuel Inlet Tube |
| RS007083 | Heat Exchanger Inlet Line |
| R0018051 | Fuel Preburner, ASI Oxidizer Line |
| R0018052 | Fuel Preburner, ASI Fuel Line |
| RS009035 | Preburner ASI Oxidizer Inlet |
| RS009016 | Preburner ASI Fuel Inlet |
| RS009086 | Preburner ASI Oxidizer Inlet Flange |
| R0010751 | Oxidizer P/B ASI Fuel Supply Line |

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Figure 5-1(b). NSTS 07700 Volume X Book 1 Section 3.2.2.1.5

| | |
|---|---|
| R0010752 | Fuel P/B ASI Fuel Supply Line |
| R0010758 | Preburner Fuel Supply Line |
| RS009168 | Nozzle, High-Pressure Oxidizer Turbopump (HPOTP) Purge Line |
| RES1001 | Hydraulic Supply Flexhose |
| RS007119 | Main Oxidizer Valve (MOV) Hydraulic Supply Manifold |
| RS007120 | MFVA Hydraulic Supply Manifold |
| RS007212 | MOVA Hydraulic Supply Manifold |

NOTE: The RS007083, Heat Exchanger Inlet Line, has been identified twice in the SSME Pressurized lines listing.

e. The RSRM aft stiffener segment shall maintain a factor of safety greater than or equal to 1.4 with respect to case buckling for the induced environments resulting from the prelaunch surface winds specified below.

| Wind Direction | Volume X Requirement | Allowable Wind Speed |
|---|---|---|
| 91 - 100 | 34 Knots | 34 Knots* |
| 101 - 110 | 34 Knots | 31 Knots |
| 111 - 120 | 34 Knots | 30 Knots |
| 121 - 134 | 34 Knots | 29 Knots |
| 135 - 140 | 31 Knots (@ 140 deg) | 28 Knots |
| 141 - 150 | 27 Knots (@ 150 deg) | 27 Knots* |

* Indicates no change to NSTS 07700, Volume X - Book 2, Appendix 10.10 requirements.

NOTE: This is applicable to Bolck II engines.

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Figure 5-1(c). NSTS 07700 Volume X Book 1 Section 3.2.2.1.5

**TABLE 3.2.2.1.5.2**

**ULTIMATE FACTORS OF SAFETY**

| Components | Factors of Safety Ultimate | |
|---|---|---|
| General structure and main propellant tanks | ≥ 1.40 | (A) (G) (H) (I) (J) (L) (M) (N) |
| Pressurized windows | | (B) |
| A. Annealed panes | | |
| Initial F. S. | ≥ 2.0 | |
| Final F. S. | ≥ 1.0 | |
| B. Tempered panes | | |
| Initial F. S. | ≥ 2.0 | |
| Final F. S. | ≥ 2.0 | |
| Pressurized manned compartments | ≥ 1.5 | |
| Pressure alone | ≥ 1.5 | |
| Main propellant tanks ET and SRB (pressure alone) | - - - | (C) (H) |
| Pressure vessels (other than main propellant tanks) | ≥ 1.5 | (A) (B) (K) |
| Pressurized lines and fittings | | |
| Less than 1.5 in. diameter | ≥ 4.0 | (E) (F) |
| 1.5 in. diameter or greater | ≥ 1.5 | |

(A) Reference Paragraph 3.2.2.1.6.

(B) Reference Paragraph 3.2.2.1.8.

(C) Factor of safety specified in element Contract End Item (CEI) and as determined by Paragraph 3.2.2.1.8.

(D) (Deleted).

(E) Design of hydraulic systems shall be in accordance with MIL-H-5440F.

(F) Lines and fittings of less than 1.5 in. diameter may be designed to a minimum factor of safety of 1.5, where advantageous to the Shuttle Vehicle, providing the rigor of design analysis and verification testing performed is equivalent to that applied to other critical systems/components. Whenever the exception allowed by this paragraph is utilized by an element, the affected system/components shall be identified along with a brief description of the analysis and testing applied in order to justify adequacy and acceptability of the lower factor of safety. All exceptions must be approved by the Manager, Space Shuttle Program.

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Figure 5-2(a). NSTS 07700 Volume X Book 1 Table 3.2.2.1.5.2

**TABLE 3.2.2.1.5.2**

**ULTIMATE FACTORS OF SAFETY - Continued**

(G) The design of the landing gear system shall be in compliance with the following structural loads design criteria:

*

| Loading Condition | Loads Definition | Factor of Safety | Material Allowable |
|---|---|---|---|
| Landing Touchdown Loads | Design | 1.0 | Yield |
| Rollout and Ground Handling | Limit | ≥ 1.4 | Ultimate |

* From MIL-A-8862, Airplane Strength and Rigidity Landplane Landing and Ground Handling Loads, Paragraph 3.1.3

(H) SRB general structure and SRB case - before separation and during BSM firing, the ultimate factor of safety shall be equal to or greater than 1.4, except reused stiffener segment stubs which are certified safe for flight by proof testing. After BSM firing, the ultimate factor of safety shall be equal to or greater than 1.25.

(I) For the ET the factor of safety for highly predictable quasi-static loads shall be equal to or greater than 1.25. Examples of such loads are steady thrust, inertial loads from steady acceleration, and weight. Thus the combined factor of safety requirement for ET structure subjected to quasi-static and not quasi-static loads is determined by:



Figure 5-2(b). NSTS 07700 Volume X Book 1 Table 3.2.2.1.5.2

**TABLE 3.2.2.1.5.2**

**ULTIMATE FACTORS OF SAFETY - Concluded**

$$FOS = \frac{(\%\ QUASI\text{-}STATIC)}{100\%} \times (1.25) + \frac{(\%\ NOT\ QUASI\text{-}STATIC)}{100\%} \times (1.4)$$

For ascent, the combined factor of safety shall be limited to a quasi-static load range of 75% to 100%. For quasi-static loads less than 75%, the factor of safety shall be 1.4. Therefore, the combined factor of safety can range from 1.25 to 1.29 for quasi-static loads ranging from 100% to 75% and is 1.4 for quasi-static loads ranging from 74% to 0. The factor of safety requirement may be determined individually for each hardware component.

(J) For the induced environments specified in NSTS 07700, Volume X - Book 2, Appendix 10.11, a factor of safety greater than or equal to 1.35 shall be acceptable for the ET/SRB forward separation bolt.

(K) This includes any component which is required by design intent to function as a pressure container following a failure in a primary pressure barrier.

(L) For preload operations, the ultimate factor of safety of the SRB holddown stud shall be equal to or greater than 1.25, based on an ultimate strength of 180,000 pounds per square inch. The factor of safety on yield shall be equal to or greater than 1.10 during preloading based on a yield strength of 150,000 pounds per square inch. Each SRB holddown stud shall be load tested to at least 1,218,000 pounds but no more than 1,228,000 pounds and not experience detrimental yielding. (Effective for STS-37, STS-39, STS-40, STS-42, and subsequent missions.)

(M) The ultimate factor of safety of the $GH_2$ vent separator bolt shall be greater than or equal to 1.30. The 1.30 factor of safety is based on a minimum separator bolt break force of 7,500 pounds at ambient temperature.

(N) The ET $LH_2$ aft dome shall be designed for stability using $K_1 = K_2 = 1.25$.

Deviation/Waiver 662 is applicable to Table 3.2.2.1.5.2.
Refer to Book 4, Active Deviations/Waivers.



Figure 5-2(c). NSTS 07700 Volume X Book 1 Table 3.2.2.1.5.2

## 5.2. External Tank (J. Neeley, MSFC)

### 5.2.1. Documentation for structural $FOS_{ult}$

The External Tank (ET) uses NSTS 07700, Volume X, *Flight and Ground System Specification - Book 1, Requirements* [7] and *CPTO1MO9A External Tank Contract End Item Specification* – Part 1 [12].

### 5.2.2. Requirements for structural $FOS_{ult}$

The ET structural $FOS_{ult}$ requirements vary from 1.25 to 1.4 and depends on how well defined the loads are known. The $FOS_{ult}$ requirements from the *External Tank Contract End Item Specification* are shown in Figure 5-3, a through i.

Note that this specification allows for "Deviations from these factors will be allowed in those instances where sufficient data on loads and strength variations are provided to establish structural integrity on a probability basis."

### 5.2.3. $FOS_{ult}$ definition

The ET $FOS_{ult}$ is defined in NSTS 07700, Volume X, Table 3.2.2.1.5.2, as:

*For the ET the factor of safety for highly predictable quasi-static loads shall be equal to or greater than 1.25. Examples of such loads are steady thrust, inertial loads from steady acceleration, and weight. Thus the combined factor of safety requirement for ET structure subjected to quasi-static and not quasi-static loads is determined by:*

$$FOS_{ult} = \frac{(\%\ \text{QUASI-STATIC})}{100\%} \times (1.25) + \frac{(\%\ \text{NOT QUASI-STATIC})}{100\%} \times (1.4)$$

*For ascent, the combined factor of safety shall be limited to a quasi-static load range of 75% to 100%. For quasi-static loads less than 75%, the factor of safety shall be 1.4. Therefore, the combined factor of safety can range from 1.25 to 1.29 for quasi-static loads ranging from 100% to 75% and is 1.4 for quasi-static loads ranging from 74% to 0. The factor of safety requirement may be determined individually for each hardware component.*

Note this definition deviates from the standard definition used in the aerospace industry and NASA–STD-5001.

### 5.2.4. Waiver or deviations from this requirement

There are no current waivers for flight structural $FOS_{ult}$. There is one retired flight $FOS_{ult}$ waiver, waiver # 662. This waiver covered ET stainless steel tubing, helium inject tubing, intertank purge lines, and nose cone purge lines. The waiver was only applicable for ET 66 and ET-71 through ET-75 and is therefore retired. Waiver #662 is shown in Figure 5-4, a through d.

Although ET does not have any current waivers, there are many components on the ET that have a $FOS_{ult}$ less than the 1.4 aerospace standard. The ET project requirements allow a $FOS_{ult}$ as low as 1.25 (reference Figure 5-3[†]) if the load is "well defined". Components with a $FOS_{ult}$ less than 1.4 are listed in Table 5-2.

**Table 5-2. ET Components with FOSult Requirements less than 1.4**

| Component | $FOS_{ult}$ Requirement |
|---|---|
| Intertank Thrust Panel | 1.27 to 1.4 depending on Mach number |
| $LO_2$ Tank | 1.29 to 1.4 depending on Mach number |
| Aft SRB Attach Fitting[1] | 1.34 |
| Note: 1) The $FOS_{ult}$ relaxation was only applicable to pre-Super Light Weight Tanks (SLWT). The current SLWT $FOS_{ult}$ requirement is 1.4. | |

Additionally, there is one waiver and one deviation for an item of ET Ground Support Equipment, the Ground Umbilical Carrier Assembly.

### 5.2.5. Waivers or deviations documentation

NSTS 07700, Volume X, Book 4, *Flight and Ground System Specification, Active Deviations/Waivers* [7], and NSTS 07700, Volume X, Book 6, *Flight and Ground System Specification, Retired Deviations/Waivers* [7].

### 5.2.6. List of current waivers to structural $FOS_{ult}$

None. However, the $FOS_{ult}$ requirements for numerous components are less than the aerospace standard of 1.4. Refer to Table 5-2 for a list of components that have a $FOS_{ult}$ less than 1.4.

[†] In Figure 5.3(d), the equivalent FOS is defined as
Equivalent FOS = [ ( % Quasistatic loads ) * 1.25 + ( % Not quasistatic loads ) * 1.4 ] / (Total limit loads).
This definition is incorrect. The correct definition is
Equivalent FOS = [ ( % Quasistatic loads ) * 1.25 + ( % Not quasistatic loads ) * 1.4 ] / 100.

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3.2.1.5.1.1 Interface Performance- The ET structural subsystem shall meet the interface performance requirements of ICDs specified in Paragraph 3.6 of this EIS.

3.2.1.5.2 Performance Requirements.

3.2.1.5.2.1 Fatigue - Safe Life design shall be adopted for all major load-carrying structures. These structures shall be capable of surviving without failure one proof test cycle and a total number of mission cycles that is a minimum of four (4) times greater than the total number of mission cycles expected in service (shown by analysis or by test through a rationally derived cyclic loading and temperature spectrum). One (1) mission cycle shall be that interval beginning with events just after tank proof test and ending 60 seconds after Orbiter/ET separation. This does not preclude fail-safe structural features.

3.2.1.5.2.2 Design Factors of Safety - The design factors of safety defined in Table 3.2.3 shall be applied to ET system, subsystem or component limit loads or pressures to obtain the design loads and pressures. The combined factor of safety requirement for ET Structure subjected to quasi-static and not quasi-static loads is determined by:

$$FOS = \frac{(\%\ \text{Quasi-Static}) \times (1.25)}{100\%} + \frac{(\%\ \text{Not Quasi-Static})}{100\%} \times (1.4)$$

For ascent, the combined factor of safety shall be limited to a quasi-static load range of 75% to 100%. For quasi-static loads less than 75%, the factor of safety shall be 1.4. Therefore, the combined factor of safety can range from 1.25 to 1.29 for quasi-static loads ranging from 100% to 75% and is 1.4 for quasi-static loads ranging from 74% to 0%. The factor of safety requirement can be determined individually for each hardware component, but must be approved and documented in the EIS.

Individual Hardware Components include the following:

1. The Intertank Thrust Panel has a revised factor of safety (FOS) due to the load mix for well-defined loads between mach > 1.55 and mach < or = 1.8. At mach 1.55 the factor of safety is 1.4, at mach 1.8 the factor of safety is 1.27, and in between the factor of safety is interpolated linearly. Between mach > 1.8 and mach < or = 2.2 the factor of safety is 1.27.

2. The LO2 Tank has a revised factor of safety (FOS) due to the load mix for well-defined loads between mach > 1.55 and mach < or = 1.8. At mach 1.55 the factor of safety is 1.4, at mach 1.8 the factor of safety is 1.29, and in between the factor of safety is interpolated linearly.

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Figure 5-3(a). ET $FOS_{ult}$ Requirements

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Deviations from these factors will be allowed in those instances where sufficient data on loads and strength variations are provided to establish structural integrity on a probability basis. Requests for deviations with supporting data will be forwarded to MSFC for approval prior to implementation.

Elongation criteria rather that the yield factors of safety specified in Table 3.2.3 may be applied with the following restrictions:

a. The structural integrity of the component affected shall be demonstrated by adequate analysis or test.
b. There shall be no deformations that adversely affect the function of the component.
c. The service life requirements or paragraph 3.2.1.5.2.1 shall be met.

The design factors of safety shall be applied to loads derived from the environment specified for nominal trajectories in Paragraphs 3.2.7.2, Induced Environments, and 3.2.7.1, Natural Environments Design Requirements, of this End Item Specification. Unless otherwise noted, loads derived from off-nominal conditions shall not have the factors defined in Table 3.2.3 applied for design purposes except for one SSME out or the failure of a single MPS flow control valve (FCV) during nominal ascent. Instead, off-nominal loads shall be assessed against structural capability derived from nominal loads to determine the factor of safety that would exist should a failure occur. One SSME out shall be based on the same Factor of Safety as no failure case. NASA shall be advised on a case by case basis whenever the factor of safety for failure modes is less than that specified for the nominal case.

Note: See Appendix 40 for ET 96 thru ET 606 (SLWT) Requirement.

3.2.1.5.2.3 Deleted

3.2.1.5.2.4 External Tank (ET) Entry Heating - To ensure safe disposal of the ET and a safe separation distance between the orbiter and ET after orbiter separation, the ET shall be designed so that the propellant tank factor of safety shall not decrease below 1.0 following ET/Orbiter separation for the normal and the intact abort missions until safe separation distance/entry altitude are achieved as per the requirements identified in paragraph 3.2.1.5.2.5. The heating environments for ascent, entry heating trajectories, and heating environments for entry are identified in paragraph 3.2.7.2 in the basic document and Appendix 40.

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Figure 5-3(b). ET $FOS_{ult}$ Requirements

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TABLE 3.2.3
DESIGN FACTORS OF SAFETY AND PROOF FACTORS

| COMPONENT | FACTORS OF SAFETY | | MINIMUM PROOF FACTORS (Use Temperature) (Note 1) | |
|---|---|---|---|---|
| | ULTIMATE (Note 2) | YIELD | FRACTURE CONTROLLED | NOT FRACTURE CONTROLLED |
| 1. General Structure | | | | |
| Limit Load | | | | |
| • Well Defined | 1.25 | 1.10 | N/A | N/A |
| • Other | 1.40 | 1.10 | N/A | N/A |
| 2. Main Propellant Tanks | | | | |
| (a) Limit Load (See Para.6.1) | | | | |
| • Well Defined | 1.40 | 1.10 | 1.05 | 1.05 |
| • Other | 1.40 | 1.10 | 1.05 | 1.05 |
| (b) LH2 Tank Aft Dome Elastic Buckling | 1.25 | N/A | N/A | N/A |
| 3. Propulsion System | | | | |
| (a) Propellant Feed lines and all other lines greater than 1.25 inch diameter, the more critical of: | | | | |
| • Limit Pressure | 1.50 | 1.25 | 1.20 | 1.20 |
| • Limit Load | 1.40 | 1.10 | 1.05 | 1.05 |
| (b) Lines Less Than 1.50 inch diameter: | | | | |
| • Limit Pressure (Notes 3,4,9) | 4.00 | 1.25 | 1.20 | 1.20 |
| (c) Actuating Cylinders, Valves, Filters, and Switches | | | | |
| • Limit Pressure | 2.00 | 1.50 | 1.50 | 1.50 |

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Figure 5-3(c). ET $FOS_{ult}$ Requirements

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TABLE 3.2.3 (continued)
DESIGN FACTORS OF SAFETY AND PROOF FACTORS

NOTES:

1. To obtain proof load or proof pressure, multiply the proof factor by the limit load or limit pressure. There shall be no detrimental yielding at proof load or proof pressure.

   To determine proof factors for temperatures other than use temperatures, use the following equations:

FRACTURE CONTROLLED COMPONENTS:

$$\text{Proof Factor (Test Temperature)} = \frac{K_{IC} \text{ of Material @ Proof Temperature}}{K_{IC} \text{ of Material @ Use Temperature}} \times \text{Proof Factor (Use Temperature)}$$

NON-FRACTURE CONTROLLED COMPONENTS:

$$\text{Proof Factor (Test Temperature)} = \frac{\text{Fty of Material @ Proof Temperature}}{\text{Fty of Material @ Use Temperature}} \times \text{Proof Factor (Use Temperature)}$$

Refer to MMC-ET-SE13 for definition of fracture controlled and not fracture controlled components.

Note: See Appendix 40 for ET 96 thru ET 606 (SLWT) Requirement. **SCN 445**

2. Ultimate Factor of Safety Application:

   Use Factor of Safety = 1.25 for quasi-static loads.
   Use Factor of Safety = 1.40 for not quasi-static loads.

   The equivalent Factor of Safety is derived by the equation:

$$\text{Equivalent Factor of Safety} = \frac{(\%\text{ Quasi-Static Loads})(1.25) + (\%\text{ Not Quasi-Static Loads})(1.4)}{\text{Total Limit Loads}}$$

   The Equivalent Factor of Safety must be between the limits 1.25 and 1.40.

   Should the Equivalent Factor of Safety exceed 1.40, the total limit load will be multiplied by a Factor of Safety of 1.40.

   Should the Equivalent Factor of Safety be less than 1.25, the total limit load will be multiplied by a Factor of Safety of 1.25.

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Figure 5-3(d). ET $FOS_{ult}$ Requirements

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TABLE 3.2.3 (continued)
DESIGN FACTORS OF SAFETY AND PROOF FACTORS

NOTES:

3. Design of hydraulic systems shall be in accordance with MIL-H-5440.

4. Lines and fittings of less than 1.5 inch diameter may be designed to a minimum Factor of Safety of 1.50, where advantageous to the Shuttle vehicle, providing the rigor of design analysis and verification testing performed is equivalent to that applied to other critical systems/components. Whenever the exception allowed by this paragraph is utilized by an element, the affected system/component shall be identified along with a brief description of the analysis and testing applied in order to justify adequacy and acceptability of the lower Factor of Safety. All exceptions are to be approved by the program manager.

5. The Aft SRB attach fitting at the shear pin interface of the 2058 Frame Chord has an ultimate bearing Factor of Safety of 1.34 in lieu of 1.40.

6. The distributed aeropressures specified in MSFC Letter SA32/1238-88 per RI letter 87MA1409 and NASA/JSC Letter WE2-87-144 have been identified as being incorrect. These incorrect IVBC-3 loads result in a 1.01 factor of safety for the Frame Shear Web (station 1130). Preliminary revised data is equal to 1.71 factor of safety.

7. Deleted. **SCN 409**

8. Deleted.

9. PRCBD S022050VR1 authorized an Ultimate Factor of Safety of 1.50 against ICD-2-0A002 maximum operating pressure, for ET Intertank and Nose Cone Purge Systems.

10. Deleted.

11. Deleted. **SCN 409**

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Figure 5-3(e). ET $FOS_{ult}$ Requirements

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3.2.1.5.3 Combined Loads - The ET structural design shall exclude the use of pressure stabilized structures with the exception of main propulsion tanks during flight and during periods as specified in ICD-2-12001 and ICD-2-0A002. Pressure load shall not be used in ground operations analyses when it relieves or increases stability, except as noted above. The mechanical, external, thermally induced, and internal pressure loads shall be combined in a rational manner according to the equations given in Paragraph 6.1 to determine the design loads. In circumstances where certain loads (stresses) have a relieving, stabilizing or otherwise beneficial effect on structural load capability, the minimum expected value of such loads shall be used and shall not be multiplied by the factor of safety in calculating the design yield or ultimate load. (Except as shown in Note (1) below.) For example, the ultimate compressive load in pressure vehicle tankage shall be calculated as follows:

Ultimate Load = Safety Factor x Body Loads - Minimum Expected Pressure Load

Any other loads induced in the structure, e.g., during manufacturing, shall be combined in a rational manner.

Note (1): For LO2 Tank on the pad with propellants loaded, Ultimate Load = Safety Factor x (Body Loads - Minimum Expected Pressure Loads).

3.2.1.5.4 Allowable Mechanical Properties - The ET shall be designed using the applicable allowable mechanical properties of MIL-HDBK-5, MIL-HDBK-17, or NASA approved supplier guaranteed properties. Where values for mechanical properties of new materials or joints and where the properties of existing materials or joints in new environments are not available, they shall be determined analytically or by test. Where tests are required, they shall be of sufficient number to establish values for the mechanical properties on a statistical basis. The effects of temperatures, thermal cycling and gradients, and detrimental environments shall be accounted for in defining allowable mechanical properties. Material "A" (99 percent exceedance with 95 percent confidence) allowable values shall be used in all applications where failure of a single load path would result in loss of structural integrity. Any new design, Stress Analysis Revisions, or Materials Review Board actions after August 30, 1992 shall be in accordance with MIL-HDBK-5.

Note: See Appendix 40 for ET 96 thru ET 606 (SLWT) Requirement. **SCN 445**

3.2.1.5.4.1 Unavailable Allowable Mechanical Properties or Unavailable Properties of Existing Material in New Environment - Not Applicable.

Note: See Appendix 40 for ET 96 thru ET 606 (SLWT) Requirement. **SCN 445**

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Figure 5-3(f). ET $FOS_{ult}$ Requirements

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**APPENDIX 40**

EXTERNAL TANK 96 & UP (SUPER LIGHTWEIGHT) UNIQUE REQUIREMENTS

40.0 SCOPE

This appendix establishes the changes to the basic requirements of this specification which are peculiar to External Tanks 96 thru 606 (SLWT). If there are no changes in requirements from EIS to Appendix 40 the word "Applicable" is identified after the requirement title. **SCN 409**

40.1 ET Differences - ET 96 thru ET 606. **SCN 409**

Add the following subparagraphs:

1.0 SCOPE - Applicable.

1.1 GENERAL - Applicable.

2.0 APPLICABLE DOCUMENTS - Applicable.

3.0 REQUIREMENT

3.1 CEI Definition - The current EIS Part I requirements are applicable as specified herein unless otherwise written in this appendix.

3.1.1 General - Applicable.

Table 3.1.1
REQUIREMENTS IDENTIFICATION MATRIX

Applicable

3.1.2 Deleted.

3.1.3 Deleted.

3.1.4 Organizational and Management Relationships - Applicable.

3.1.5 Systems Engineering Requirements - Applicable.

3.1.6 Government Furnished Property (GFP) List - Applicable.

3.1.7 Critical Components - Applicable. **SCN 409**

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Figure 5-3(g). ET $FOS_{ult}$ Requirements

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3.2.1.4.1.1 Interface Performance - Applicable.

3.2.1.4.2 Mating Linkage - Applicable.

3.2.1.5 Structural Subsystem Performance - Applicable.

3.2.1.5.1 General - Applicable.

3.2.1.5.1.1 Interface Performance - Applicable.

3.2.1.5.2 Performance Requirements - Applicable.

3.2.1.5.2.1 Fatigue - Applicable.

3.2.1.5.2.2 Design Factors of Safety- Applicable. **SCN 409R1**

Table 3.2.3

DESIGN FACTOR OF SAFETY AND PROOF FACTORS

Applicable

SCN 409R1 04/08/98

40-8

Figure 5-3(h). ET $FOS_{ult}$ Requirements

APPENDIX 40
PART I
Specification No. CPTO1MO9A
Revision: Basic
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NOTES:

1. To obtain proof or proof pressure, multiply the proof factor by the limit load or limit pressure. There shall be no detrimental yielding at proof load or proof pressure.

To determine proof factors for temperatures other than use temperatures, use the following equations:

**FRACTURE CONTROLLED COMPONENTS:**

$$\text{Proof Factor (Test Temperature)} = \frac{K_{IC}\text{* of Welded Material @ Proof Temperature}}{K_{IC}\text{* of Welded Material @ Use Temperature}} \times \text{Proof Factor (Use Temperature)}$$

**NOT FRACTURE CONTROLLED COMPONENTS:**

$$\text{Proof Factor (Test Temperature)} = \frac{\text{Fty of Material @ Proof Temperature}}{\text{Fty of Material @ Use Temperature}} \times \text{Proof Factor (Use Temperature)}$$

* For Al 2195 parent metal and welds, the $K_{IE}$ values, the toughness of a surface flaw may be used instead of $K_{IC}$ values. The initial flaw size shall be defined in the Fracture Control Plan MMC-ET-SE13. For Al 2195, the proof factors shall be verified by simulated service testing.

Refer to MMC-ET-SE13 for definition of fracture controlled and not fracture controlled components.

NOTES: 2 through 4 and 9 - Applicable. **SCN 423**

3.2.1.5.2.3 Deleted.

3.2.1.5.2.4 External Tank(ET) Entry Heating - Applicable.

3.2.1.5.2.5 ET/Orbiter Safe Separation Distance and ET Rupture Altitude - For the SLWT (ET-96 thru 606) condition that minimizes the ET rupture time, the SLWT shall not rupture prior to 177 seconds after ET separation. For the SLWT condition that minimizes the relative distance between the ET and Orbiter at rupture, the SLWT shall not rupture prior to 191 seconds after ET separation.

SCN 423 03/29/99

40-9

Figure 5-3(i). ET $FOS_{ult}$ Requirements

**DEVIATIONS/WAIVERS AUTHORIZED FOR REQUIREMENTS CONTAINED IN THIS DOCUMENT – Continued**

**662. REQUIREMENT:** Paragraph 3.2.2.1.5.2 Ultimate Factors of Safety. The ultimate factors of safety given in Table 3.2.2.1.5.2 shall be

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Figure 5-4(a). ET $FOS_{ult}$ Retired Waiver 662

**DEVIATIONS/WAIVERS AUTHORIZED FOR REQUIREMENTS CONTAINED IN THIS DOCUMENT – Continued**

used for the Shuttle Vehicle structure. The following specific conditions are allowed:

f. The ultimate factor of safety of 1.50 against ICD max pressure conditions is acceptable for ET intertank and nose cone purge systems.

MMC has performed a stress analysis for the purge system components for maximum operating and relief pressure conditions with the results as follows:

1. All components satisfy ET-EIS requirements for max ICD operating pressure
2. All components have factors of safety (F.S). ±1.0 for relief pressure
3. All components have adequate proof factors for both pressure conditions

NOTE: EXCEPTION: For ET-66 and ET-71 thru ET-75, the ultimate factor of safety of 1.5 may be excepted to allow flight use of external tank nose cone purge line 1/4 inch tubing which has demonstrated an ultimate factor of safety of 1.37.

Table 3.2.2.1.5.2 Ultimate factors of safety requires that pressurized lines and fittings less than 1.5 inches diameter have an ultimate factor of safety greater than or equal to 4.0 and lines and fittings greater than or equal to 1.5 inches have an ultimate factor of safety greater than or equal to 1.5.

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Figure 5-4(b). ET $FOS_{ult}$ Retired Waiver 662

DEVIATIONS/WAIVERS AUTHORIZED FOR REQUIREMENTS
CONTAINED IN THIS DOCUMENT – Continued

**TABLE 3.2.2.1.5.2**

**ULTIMATE FACTORS OF SAFETY**

| COMPONENTS | FACTORS OF SAFETY ULTIMATE | |
|---|---|---|
| General structure & main propellant tanks | ≥1.40 | (A) (G) (H) (I) (J) (L) (M) (N) (B) |
| Pressurized windows | | |
| A. Annealed panes | | |
| Initial F. S. | ≥2.0 | |
| Final F. S. | ≥1.0 | |
| B. Tempered panes | | |
| Initial F. S. | ≥2.0 | |
| Final F. S. | ≥2.0 | |
| Pressurized manned compartments | ≥1.5 | |
| Pressure alone | ≥1.5 | |
| Main propellant tanks ET & SRB (pressure alone) | - - - | (C) (H) |
| Pressure vessels (other than main propellant tanks) | ≥1.5 | (A) (B) (K) |
| Pressurized lines and fittings | | |
| Less than 1.5 in. diameter | ≥4.0 | (E) (F |
| 1.5 in. diameter or greater | ).1.5 | |

**WAIVER:** The above requirement is waived for 3/8 inch external tank stainless steel tubing to allow an ultimate factor of safety of 1.75 for helium inject tubing, 1.35 for intertank purge, and 1.37 for the nose cone purge lines.

**RATIONALE:** Factor of safety demonstrated by proof test exceeds ultimate requirements.

- Helium inject: Ultimate required = 4.0
  Demonstrated F. S. = 15.95
- Intertank purge: Ultimate required = 1.5
  Demonstrated F. S. = 3.71
- Nose cone purge: Ultimate required = 1.5
  Demonstrated F. S. = 3.75

Any failure of suspect 3/8" diameter tubing during prelaunch ground operations will be detected.

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Figure 5-4(c). ET $FOS_{ult}$ Retired Waiver 662

DEVIATIONS/WAIVERS AUTHORIZED FOR REQUIREMENTS
CONTAINED IN THIS DOCUMENT – Continued

- Temperature sensors in N/C and I/T would detect leak and allow safing procedures to be performed.
- Facility helium differential pressure would detect leak and allow for safing procedures to be performed.

One on/off pressure cycle during cryo loading activities.

- 1000 plus cycle capability based on fracture analysis.

Helium inject, nose cone purge and intertank purge 3/8 in. stainless steel tubing fabricated from lot HSN is acceptable for flight.

**EFFECTIVITY:** ET-74

**AUTHORITY:** Space Shuttle PRCBDs S082908A, dated 11/10/95 and S082908AR1, dated 11/20/95.

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Figure 5-4(d). ET $FOS_{ult}$ Retired Waiver 662

## 5.3. Other Space Shuttle Program Elements (J. Kramer-White, JSC)

This section describes details for the Space Shuttle Program elements other than the orbiter and the ET discussed previously. These elements include the SRB, SRM, and the SSME.

### 5.3.1. Document(s) for structural $FOS_{ult}$

The structural $FOS_{ult}$ for all space shuttle systems are defined in NSTS 07700 Volume X, *Flight and Ground System Specification - Book 1, Requirements* [7]. The $FOS_{ult}$ requirements are detailed in Section 3.2.2.1.5, *Structure.* Section 3.2.1.5 is reproduced and provided in Figure 5-1, a through c.

### 5.3.2. Requirements for structural $FOS_{ult}$

Ultimate FOSs are listed in NSTS 07700, Volume X, Book 1, Table 3.2.2.1.5.2, *Ultimate Factors of Safety*, which is reproduced and provided in Figure 5-2, a through c. There are no requirements on Yield FOS.

Generally, the structure $FOS_{ult}$ requirement is greater than or equal to 1.4, with more specific requirements for glass, pressurized compartments, pressure vessels and pressurized lines, landing gear and exceptions for some specific SRB elements (i.e., SRB after separation > 1.25).

Note that if a requirement has been changed to allow an exception, then it is NOT considered a waiver or deviation. Therefore, a program can cite an exception because general/original requirements are not met. Such situations are cited in notes (F) through (M) of Table 3.2.2.1.5.2, which is reproduced and provided in Figure 5-2, a through c.

### 5.3.3. $FOS_{ult}$ definition

See relevant definitions in NSTS 07700, Volume X, Book 1, Section 3.2.2.1.5.1, *Definitions* [7], but specifically, $FOS_{ult}$ is defined as:

$$FOS_{ult} = \text{Ultimate load/Limit load}$$

### 5.3.4. Waivers or deviations from this requirement

There are a total of 5 waivers: Waivers #387, 448, 449, 512 and 692.

<u>Note</u>: **Since the time of this audit, the Shuttle Program has invested considerable effort to eliminate FOS waivers as part of the return-to-flight activity. Recently, these efforts resulted in the retirement of waivers #387, 448, and 449.**

### 5.3.5. Waivers or deviations documentation

NSTS 07700, Volume X, Book 4, *Flight and Ground System Specification, Active Deviations/Waivers* [7], and NSTS 07700, Volume X, Book 6, *Flight and Ground System Specification, Retired Deviations/Waivers* [7].

#### 5.3.6. List of current waivers to structural $FOS_{ult}$

Appendix B of this paper lists the current waivers for space shuttle elements.

### 5.4. X-43 (M. Kehoe, DRFC)

#### 5.4.1. Documentation for structural $FOS_{ult}$

The HYPER-X structural FOS requirements are documented in Hyper-X document HX-280 Rev G Hyper-X, Flight System Performance Requirements [13].

Hyper-X Launch Vehicle (HXLV) delivers the Hyper-X Research Vehicle (HXRV) and adapter to its flight separation point. After that point the HXRV will fire its scramjet propulsion system while traveling at hypersonic speeds. Thus the two vehicles have vastly different FOS.

#### 5.4.2. Requirements for structural FOS

Refer to Tables 5-3 and 5-4.

**Table 5-3. HXLV Requirements for Boost and Free-Flight**

| Factors of Safety | | |
|---|---|---|
| Mechanical loads | Yield | 1.1 |
| | Ultimate | 1.5 |
| Thermal loads *,** | Yield | 1.0 |
| | Ultimate | 1.0 |
| * Refer to HXGFI-01 Section H7010-M7-01-ST for additional requirements on uncertainty factors for thermal analysis.<br>** The FOS defined for thermal loads shall be applied to internal stresses within a component. Loads that cross a mechanical joint and the loads within that joint shall use as a minimum the FOS for mechanical loads. | | |

**Table 5-4. HXRV Requirements for Captive Carry Flight**

| Factors of Safety | | |
|---|---|---|
| Mechanical loads | Metallic Structures | 2.25 |
| | Non-metallic Structures | 3.0 |

#### 5.4.3. $FOS_{ult}$ definition

The project uses the following definition:

$$FOS_{ult} = \text{Ultimate Load/Limit Load}$$

#### 5.4.4. Waiver or deviations from this requirement

There are no waivers or deviations for the X-43 project.

#### 5.4.5. Waivers or deviations documentation

There are no waivers for structural $FOS_{ult}$. Normally deviation and waiver documentation is managed by the Project led by the Configuration Control Board (CCB). The CCB consists of representatives from the project, engineering, quality assurance, safety, and science (if applicable). The CCB reviews the waiver and waiver rationale and approves or rejects the waiver.

#### 5.4.6. List of current waivers to structural $FOS_{ult}$

There are no waivers or deviations for the X-43 project.

### 5.5. Swift Spacecraft (A. Posey, GSFC)

The Swift program is a GSFC program managed out of the Explores Program Office (Code 410). There are three scientific instruments on the Observatory. Goddard is building one of the instruments (BAT - Burst Alert Telescope) in-house while the two other instruments are being provided by Penn State University [Ultra-Violet Optical Telescope (UVOT) and X-ray Telescope (XRT)] in partnership with donated hardware being provided by Mullard Space Science Laboratory and the University of Leicester in the (UK), and the Osservatorio Astronomico di Brera (Italy). The spacecraft is being procured through the Goddard Rapid Spacecraft Development Office (RSDO) with Spectrum-Astro being responsible for spacecraft bus and system integration.

#### 5.5.1. Documentation for structural $FOS_{ult}$

For the Instruments and Optical bench, the minimum FOSs are defined in the Swift Instrument Requirement Document (IRD), Section 3.8. The contract specification for the Spectrum-Astro bus did not specify minimum FOSs. The minimum FOSs are specified in Spectrum-Astro's own internal design document (1143-EW-M22361).

#### 5.5.2. Requirement for structural $FOS_{ult}$

The FOS requirements are tracked in the project's Requirement Verification Matrix (RVM) and verified at component delivery when the End Item Data Package (EIDP) is submitted and reviewed. The RVM points to the particular stress analysis or applicable report.

### 5.5.3. $FOS_{ult}$ Definition

Table 5-5 details the various FOSs for the different Swift Observatory elements.

**Table 5-5. FOS for Swift Observatory Elements**

| Swift Observatory Element | $FOS_{yield}$ | $FOS_{ult}$ | $FOS_{yield}$[1] | $FOS_{ult}$[1] |
|---|---|---|---|---|
| BAT (GSFC H/W) | 1.25 | 1.4 | 1.6 | 2.0 |
| UVOT | 1.25 | 1.4 | 1.6 | 2.0 |
| XRT | 1.25 | 1.4 | 1.6 | 2.0 |
| OPTICAL BENCH (GSFC H/W) | 1.25 | 1.4 | 1.6 | 2.0 |
| S/C BUS STRUCTURE (SPECTRUM-ASTRO) | 1.25 | 1.4 | 1.6 | 2.0 |
| MGSE[3] | 3.0 | 5.0 | | |

[1]These FOSs are for hardware elements that were not qualified during the strength test program and were therefore qualified through analysis only.

[2] The instrument was "build to print" that was qualified by similarity from a previous program.

[3]Mechanical Ground Support Equipment

### 5.5.4. Waivers or deviations from this requirement

There are no structural $FOS_{ult}$ waivers.

### 5.5.5. Waiver or deviations documentation

Waivers are documented through a Project led by the CCB. The CCB consists of representatives from the project, engineering, quality assurance, safety, and science (if applicable). The CCB reviews the waiver and waiver rationale and approves or rejects the waiver.

### 5.5.6. List of current waivers to structural $FOS_{ult}$

There are no structural $FOS_{ult}$ waivers.

### 5.6. Audit Summary

Table 5-6 provides a summary of the Project Audited, the Structural Ultimate $FOS_{ult}$ used and the number of deviations to the required $FOS_{ult}$.

**Table 5-6. Summary $FOS_{ult}$ and Waivers for all Programs Reviewed**

| Program/Project | Required $FOS_{ult}$ | Current Waivers |
|---|---|---|
| Orbiter | 1.4 | None |
| ET | 1.25 to 1.4 | None |
| SRB, SRM, SSME | 1.4 | 2SRB[1], 2 SRM[1], 1ET (retired) |
| X-43 | 1.5 | None |
| Swift Spacecraft | 1.4 | None |
| Note 1) Since the time of the original audit both SRB waivers and 1 SRM waiver above have been retired. | | |

## 6. DISCUSSION AND RECOMMENDATIONS

The audit discovered that all of the projects used NASA-STD-5001 for the overall structure $FOS_{ult}$ requirements but ultimately customized these requirement(s) into their own internal requirements document. In addition to the aerospace $FOS_{ult}$ requirement of 1.4, the aeronautical project reviewed used the higher FAA requirement of structural $FOS_{ult} \geq 1.5$.

Most of the projects surveyed met the NASA-STD-5001 structural $FOS_{ult}$ value of 1.4. The exception was the Space Shuttle Program's non-orbiter projects. There were five active waivers for structural $FOS_{ult}$. (Since the time of the original audit the Space Shuttle Program has undertaken considerable effort to eliminate $FOS_{ult}$ waivers as part of the return-to-flight activity. This has resulted in retirement of three of the five waivers discussed previously.) In addition to the waivers there were several examples of $FOS_{ult}$ requirement relaxation below the 1.4 standard. When the requirement was relaxed, there was no need for a waiver.

The justification for a relaxed or waived structural $FOS_{ult}$ varied, but in all cases was limited at best. An often cited justification was the "loads were well known". This was a necessary condition but insufficient as the "loads were well known" was a requisite for originally reducing the $FOS_{ult}$ from 1.5 to 1.4 and cannot be used again to further reduce the $FOS_{ult}$ below 1.4. An uncertainty factor, applied to analysis results, accounts for the load knowledge fidelity. As the loads become well known, the uncertainty factor reduces to unity (reference NASA-STD-5002 "Load Analysis of Spacecraft", paragraph 4.2.4.2 [14]). Load knowledge fidelity should not impact the value of the $FOS_{ult}$ (reference NASA-STD-5001, paragraph 1.2). Since the $FOS_{ult}$ requirement is derived from historical data and not from fundamental physics, one cannot simply extrapolate outside of the known database when no valid, statistically significant, data exists. To justify the waiver in the absence of a physics/mathematical model, only the generation of a statistically significant data set can be used, or unknowns significantly reduced (i.e., test verified model, measured loads, etc.). It is of concern that engineering judgment may often be used that has neither mathematical basis nor statistically significant test data to support a technically sound determination.

Based on the work performed during the course of this action item, five recommendations are presented below.

### 6.1. $FOS_{ult}$ when testing is not available

Although NASA-STD-5001, Section 4.1.2.3, provides general information on test versus no-test options, it does not provide specific $FOS_{ult}$ guidance for no-test hardware. GSFC General Environmental Verification Specification (GEVS) [6] provides specific guidance on no-test $FOS_{ult}$ (2.0 for Yield and 2.6 for Ultimate) and some Projects (Swift spacecraft) use a higher $FOS_{ult}$ when qualification is performed by analysis only. Other Centers do not have such guidelines and, therefore, no single number, if any, is used for no-test hardware. Whenever possible, higher $FOS_{ult}$ values are recommended when qualification is performed using analysis only. It is recommended to update NASA-STD-5001 to include specific guidance and suggested $FOS_{ult}$ value required for no-test hardware.

### 6.2. Requirement Relaxation

In rare instances it was observed that to maintain a positive $MOS_{ult}$, the standard $FOS_{ult}$ requirement was relaxed instead of issuing a waiver. With this practice one loses visibility into the rationale behind the modification. Additionally, NASA loses the ability to look at waivers across the agency to gather statistical evidence on how often the standard $FOS_{ult}$ is reduced.

It is recognized that unique situations may exist where the $FOS_{ult}$ requirements, based on project maturity, can be revised from the 1.4 value with negligible increased risk. The specific case involves the single use Shuttle External Tank (ET) Project where a comprehensive operational database of flight experience, manufacturing process characterization, analytical modeling, and test validation justified the change of the $FOS_{ult}$ from 1.4 to 1.25 for static pressure loads. However, the $FOS_{ult}$ requirement change should have been documented by the generation of a deviation and not a contractual requirements relaxation. This allows system visibility on the rationale used to justify the alteration and appreciation of any potential synergistic affects.

It is recommended that Projects not relax requirements to meet hardware performance, but rather utilize the waiver and deviation processes when appropriate.

### 6.3. $FOS_{ult}$ Waivers Not a Precedent

Waivers should be considered a *one time exception*. For reusable (i.e., Space Shuttle Program elements) or flights of recurring hardware (i.e. off the shelf spacecraft bus) a waiver should not be a precedent to continue flying with a deficiency, but an indication that corrective action must be taken.

### 6.4. Maintaining FOS Over the Life of a Program

Structural strength or load carrying capability is often only computed one time during the life of the hardware. While this may be appropriate for elements that are one time use, or have only a very limited life, this is not an appropriate approach for the certification of an element that will be utilized for many years. Over the life of a system, reduction of the original Allowable Ultimate Load may occur for several reasons:

- Degradation of materials or coatings (e.g.corrosion, atomic oxygen, etc.)
- Wear and Tear/Operationally induced damage
- Maintenance induced damage

Reduction of the Allowable Ultimate Load results in a corresponding reduction of $MOS_{ult}$. To maintain a positive $MOS_{ult}$, the $FOS_{ult}$ is often reduced.

NASA-STD-5001 should be modified to include requirements for periodic re-certification of hardware capability throughout a program's life. While programs tend to recognize the impact of changing missions and therefore loads as a valid reason for re-computing the MOS and potentially FOS, this revalidation process should also include relevant information from hardware inspection, problem reports and material review board (MRB) actions as it relates to structural integrity.

### 6.5. Probabilistic Approaches

The $FOS_{ult}$ approach that is traditionally used can be described as illustrated in Figure 6-1. The load that is calculated on the structural component is multiplied by the $FOS_{ult}$ and the strength or equivalent material property (shown as resistance in this figure) is multiplied by a number called the knock-down factor (usually to account for presence of stress raisers such as holes, defects, etc., hot-wet conditions, etc.). The $FOS_{ult}$ are usually greater than unity while knock-down factors are less than unity. The difference between the two dashed bars shown in the figure is the MOS. This traditional approach has been proven to be useful during the past five to six decades for aerospace components.

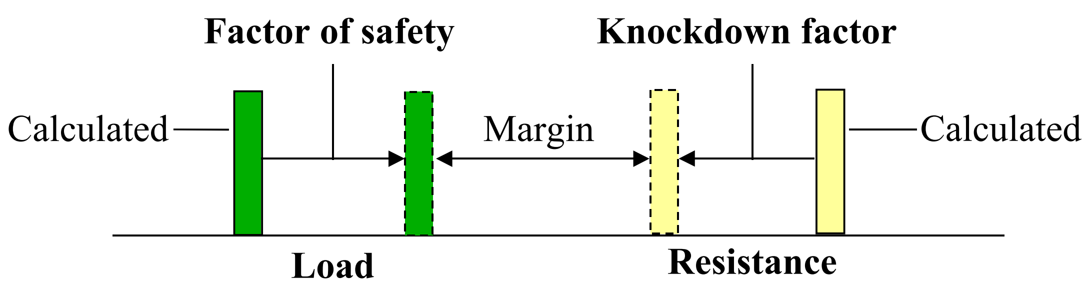


Figure 6-1. Traditional Method based on $FOS_{ult}$

Figure 6-2 illustrates an alternative to the $FOS_{ult}$ approach called the probabilistic approach or reliability-based design approach. Here both the load and the strength are characterized by probability density functions. These distributions are due to uncertainties in the loads applied and to the strengths of material of the structural component. The overlap region (where the load exceeds the strength) indicates the probability of failure.

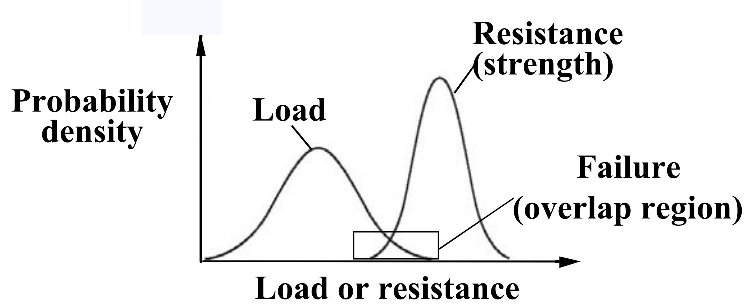


Figure 6-2. Reliability-based Design Methodology

The traditional design procedures, however, have several shortcomings. First in the traditional approach, $FOS_{ult}$ value was determined empirically and not based on any physics or mathematics. Second, measures of reliability are not available from the design process.  Consequently, it is not possible to determine the relative importance of various design options on the reliability of the component.  Third, with no measure of reliability, it is unlikely that the reliability and performance will be consistent throughout the vehicle.  This situation can lead to excess weight with no corresponding improvement in overall reliability.

An approach that has the potential to yield the degree of reliability needed in each component of a system will be beneficial to aerospace structures and structural components.  Probabilistic approaches hold excellent promise in these directions [15, 16].  Therefore, it is recommended that NASA perform further research in these areas.

**References**


1. NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware, June 21, 1996.
2. NASA-STD-5005, Design Criteria Requirements for Payloads Using the Space Shuttle, September 15, 2003.
3. NASA-STD-5003, Fracture Control Requirements for Payloads Using the Space Shuttle, October 7, 1996.
4. NASA-STD-5007, General Fracture Control Requirements for Manned Spaceflight Systems, March 13, 2001.
5. DHB-R-001, Dryden Flight Research Center Handbook For Structural Design, Proof Test, and Flight Test Envelope Guidelines, February 1999.
6. GSFC-GEVS-SE, General Environmental Verification Specification, June 1996.
7. NSTS 07700, Volume X, Books 1-6 (specifically Book 1, section 3.2.2.1.5 for structure), November 10, 1998.
8. NSTS 1700.7B, Safety and Policy Requirements for Payload using STS, January, 1989.
9. MSFC-HDBK-505A, Structural Design and Verification Requirements, January, 1981.
10. NASA MSFC ED22-OWI-001, Rev B, Organizational Instruction Strength Analysis, July 24, 2003.
11. Muller, G.E. and Clement S.J.: "Factor of Safety – USAF Design Practice", Air force Flight Dynamics Lab Wright Paterson AFB, April 1978.
12. CPT01M09-A, External Tank Contract End Item Specification – Part 1, 1980.
13. HYPER-X Flight System Performance Requirements, HX-280, Rev. G, September 9, 2003.
14. NASA-STD-5002, Loads Analyses of Spacecraft and Payloads, June 21, 1996.
15. Cruse, T.A., "Nondeterministic, Non-traditional methods (NDNTM)". NASA CR-2001-210976, 2001.
16. Zang T. A, Hemsch, M. J., Hilburger, M W., Kenny, S. P., Luckring, J. M., Maghami, P., Padula, S. L., and Stroud, W. J., "Needs and Opportunities for Uncertainty-Based Multidisciplinary Design Methods for Aerospace Vehicles", NASA TM-2002-2114602, 2002.

**Appendix A**

# Acronyms & Definitions

**Acronyms**

| | |
|---|---|
| BAT | Burst Alert Telescope |
| BSM | Booster Separation Motor |
| CAIB | Columbia Accident Investigation Board |
| CCB | Configuration Control Board |
| CLA | Coupled Loads Analysis |
| CR | Change Request |
| DFRC | Dryden Flight Research Center |
| DoD | Department of Defense |
| EIDP | End Item Data Package |
| ELV | Expendable Launch Vehicle |
| EMU | Extravehicular Mobility Unit |
| ET | External Tank |
| ETA | External Tank Attach |
| FAA | Federal Aviation Administration |
| FOS | Factor of Safety |
| $FOS_{ult}$ | Ultimate Factor of Safety |
| $FOS_{yield}$ | Yield Factor of Safety |
| GEVS | General Environmental Verification Specification |
| GSFC | Goddard Space Flight Center |
| HXLV | Hyper-X Launch Vehicle |
| HXRV | Hyper-X Research Vehicle |
| IRD | Instrument Requirement Document (Swift) |
| JSC | Johnson Space Center |
| LaRC | Langley Research Center |
| $LO_2$ | Liquid Oxygen |
| MDP | Maximum Design Pressure |
| MGSE | Mechanical Ground Support Equipment |
| MOS | Margin of Safety |
| MSFC | Marshall Space Flight Center |
| MUF | Model Uncertainty Factor |
| NASA | National Aeronautics and Space Administration |
| NESC | NASA Engineering and Safety Center |
| NSTS | National Space Transportation System |
| PA | Probabilistic Approaches |
| PRCB | Program Requirements Control Board |
| RSDO | Rapid Spacecraft Development Office |
| RVM | Requirement Verification Matrix |
| SRB | Solid Rocket Booster |
| SRM | Solid Rocket Motor |
| SSME | Space Shuttle Main Engine |

| | |
|---|---|
| UVOT | Ultra-Violet Optical Telescope |
| XRT | X-ray Telescope |

**Definitions**

**Acceptance Test**
A test performed on each article of the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, acceptance, proof, and protoflight tests are synonymous.

**Creep**
Time-dependent permanent deformation under sustained load and environmental conditions.

**Detrimental yielding**
Yielding that adversely affects the fit, form, function, or integrity of the structure.

**Factors Of Safety (Safety Factors)**
Multiplying factors to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability.

**Failure**
Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environments, or to function as designed.

**Fatigue**
The cumulative irreversible damage incurred in materials caused by cyclic application of stresses and environments resulting in degradation of load carrying capability.

**Limit Load**
The maximum anticipated load, or combination of loads, which a structure may experience during its service life under all expected conditions of operation or use.

**Maximum Design Pressure (MDP)**
The highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and, where applicable, transient pressure excursions. MDP for Space Shuttle payloads is a two-failure tolerant pressure, i.e., will accommodate any combination of two credible failures that will affect pressure during association with the Space Shuttle. MDP also accommodates the maximum temperature to be experienced in the event of an abort to a site without cooling facilities.

**Pressure Vessel**
A container designed primarily for storing pressurized gases or liquids and (1) contains stored energy of 14,240 foot-pounds (19,309 Joules) or greater, based on adiabatic expansion of a perfect gas; or (2) experiences a limit pressure greater than 100 pounds per square inch absolute (psia) (689.5 kiloPascal [kPa] absolute); or (3) contains a pressurized fluid in excess of 15 psia (103.4 kPa absolute), which will create a safety hazard if released.

**Pressurized Component**
A line, fitting, valve, or other part designed to contain pressure and that (1) is not made of glass, or (2) is not a pressure vessel, or (3) is not a propellant tank, or (4) is not a solid rocket motor case.

**Proof Test**
A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, proof, acceptance, and protoflight tests are synonymous.

**Proof Test Factor**
A multiplying factor to be applied to the limit load or MDP to define the proof test load or pressure.

**Protoflight Test**
A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, protoflight, acceptance, and proof tests are synonymous.

**Prototype Test**
A test performed on a separate flight-like structural test article to verify structural integrity of the design. Prototype tests and qualification tests are synonymous.

**Qualification Test**
A test performed on a separate flight-like structural article of each type to verify structural integrity of the design. Qualification and prototype tests are synonymous.

**Qualification Test Factor**
A multiplying factor to be applied to the limit load or MDP to define the qualification test load or pressure.

**Safety Critical**
A classification for structures, components, procedures, etc., whose failure to perform as designed or produce the intended results would pose a threat of serious personal injury or loss of life.

**Service Life**
All significant loading cycles or events during the period beginning with manufacture of a component and ending with completion of its specified use. Testing, transportation, lift-off, ascent, on-orbit operations, descent, landing and post-landing events shall be considered.

**Service Life Factor (Life Factor)**
A multiplying factor to be applied to the maximum expected number of load cycles in the service life to determine the design adequacy in fatigue or fracture.

**Ultimate Design Load**
The product of the ultimate factor of safety and the limit load. Also referred to as *Ultimate Load* and *Design Ultimate Load*.

**Ultimate Strength**
The maximum load or stress that a structure or material can withstand without incurring failure.

**Yield Design Load**
The product of the yield factor of safety and the limit load.

**Yield Strength**
The maximum load or stress that a structure or material can withstand without incurring detrimental yielding.

# Appendix B

## Summary of Waivers for Space Shuttle Elements (SRB, SRM, SSME)

Waiver process used by the Space Shuttle Program:

"When it is considered to be in the best interest by the Space Shuttle Program (SSP) element/project managers to change, waive or deviate from these requirements, an SSP Change Request (CR) shall be submitted to the Secretary of the Program Requirements Control Board (PRCB). The CR must include a complete description of the change, waiver or deviation and the rationale to justify its consideration. All such requests will be processed in accordance with NSTS 07700, Volume IV - Book 1 and dispositioned by the Manager, Space Shuttle Program, on a Space Shuttle PRCB Directive (PRCBD)."

Table B.1 presents waiver numbers 387, 448, 449, 512, 662, and 692. Note that the retired waivers are included in this table.

| Table B.1. List of Space Shuttle Element Structural FOS Waivers | | | | | | | |
|---|---|---|---|---|---|---|---|
| Num | Requirement | Element | Waiver or Deviation | Rational | Effectivity | Authority | Date |
| 387 Retired | Paragraph 3.2.2.1.5 Structure. The Shuttle Vehicle structure, including pressure vessels and mechanical systems, shall have adequate strength and stiffness, at the design temperature, to withstand limit loads and pressures without loss of operational capability for the life of the vehicle and to withstand ultimate loads and pressures at design temperature without failure. The structure shall not be designed to withstand loads, pressures or temperatures arising from malfunctions that prevent a successful abort. Major structural elements shall not be designed by nonflight conditions, i.e., conditions other than prelaunch (vehicle mating) through landing except for SRB water recovery.<br><br>Retired (Reference Space Shuttle PRCBD, S094174L, dated 8/10/04) | SRB | Waiver: The above requirement is waived for system tunnel parts with negative margins which occur during splashdown. | N/A | STS-26 thru STS-999 | Level II PRCBD S94174A | 9/10/1988 |
| 448 Retired | Paragraph 3.2.2.1.5 Structure. The Shuttle Vehicle structure, including pressure vessels and mechanical systems, shall have adequate strength and stiffness, at the design temperature, to withstand limit loads and pressures without loss of operational capability for the life of the vehicle and to withstand ultimate loads and pressures at design temperature without failure. The structure shall not be designed to withstand loads, pressures or temperatures arising from malfunctions that prevent a successful abort. Major structural elements shall not be designed by nonflight conditions, i.e., conditions other than prelaunch (vehicle mating) through landing except for SRB water recovery.<br><br>Retired (Reference Space Shuttle PRCBD S094174L, dated 8/10/04) | SRM | Waiver: APU isolation mounts (see part number below) which have a negative margin of safety at water impact. P/N 10201-0062-801(M2), S/N's V7J003, V9D002, V9D007, V9D012; P/N 10201-0061-801 (M3), V9D008, V9D010, V9D011, V8E002 | N/A | STS-26 & subs | Level II PRCBD S94554 | 9/21/1988 |
| 449 Retired | Paragraph 3.2.2.1.5 Structure. The Shuttle Vehicle structure, including pressure vessels and mechanical systems, shall have adequate strength and stiffness, at the design temperature, to withstand limit loads and pressures without loss of operational capability for the life of the vehicle and to withstand ultimate loads and pressures at design temperature without failure. The structure shall not be designed to withstand loads, pressures or temperatures arising from malfunctions that prevent a successful abort. Major structural elements shall not be designed by nonflight conditions, i.e., conditions other than prelaunch (vehicle mating) through landing except for SRB water recovery.<br><br>Retired (Reference Space Shuttle PRCBD S094174L, dated 8/10/04) | SRB | Waiver: forward skirt access door fasteners with negative margins which occur during splashdown | N/A | STS-26 & subs | Level II PRCBD S94741A | 9/21/1988 |

| Table B.1. List of Space Shuttle Element Structural FOS Waivers | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Num** | **Requirement** | **Element** | **Waiver or Deviation** | **Rational** | **Effectivity** | **Authority** | **Date** |
| 512 Open | Paragraph 3.2.2.1.8 Fracture Control. In addition to the ultimate factors of safety presented in Paragraph 3.2.2.1.5.2, designs for primary structure, windows, glass components of other subsystems, and tanks shall consider the presence of sharp cracks, crack-like flaws, or other stress concentrations in determining the life of the structure for sustained loads and cyclic loads coupled with environmental effects. Parts (other than SSME) determined to be fracture critical shall be controlled in design, fabrication, test, and operation by a formal, NASA-approved fracture control plan as specified in SE-R-0006, JSC Requirements For Materials And Processes. SSME parts determined to be fracture critical shall be subjected to fracture mechanics analysis as specified in RSS-8589. Where analysis does not demonstrate that the detectable flaw size will not grow to critical size during the service life, a risk assessment will be made to determine the acceptability of the part for flight and the conditions for this use.<br><br>SE-R-0006, Paragraph 2.4.2, Fracture Control Plan. Quality Assurance. The quality assurance system applied to fracture-critical parts will verify that materials and parts conform to engineering requirements. Specifically, the capability of Nondestructive Evaluation (NDE) techniques to reliably detect initial flaws defined by engineering will be verified based on applicable production experience or by laboratory demonstration with realistic flaws and production or inservice inspection conditions. | EMU | "Waiver: Allows exemption from Nondestructive Evaluation (NDE) of the liners for PLSS composite pressure vessels (SV778895)." | N/A | STS-26 & sub-sequent | Level II PRCBD S41427B | 2/2/1989 |
| 662 Retired | Paragraph 3.2.2.1.5.2 Ultimate Factors of Safety. The ultimate factors of safety given in Table 3.2.2.1.5.2 shall be used for the Shuttle Vehicle structure.<br><br>Retired per SSP DOC-422, dated 3/31/99. (Reference Space Shuttle PRCBD S082908A, dated 11/10/95). See Book 6. | ET | Waiver: 3/8 inch external tank stainless steel tubing to allow an ultimate factor of safety of 1.75 for helium inject tubing, 1.35 for intertank purge, and 1.37 for the nose cone purge lines | | ET-74 | Space Shuttle PRCBDs S082908A; S082908AR 1 | 11/10/1995; 11/20/95 |

| Table B.1. List of Space Shuttle Element Structural FOS Waivers | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Num** | **Requirement** | **Element** | **Waiver or Deviation** | **Rational** | **Effectivity** | **Authority** | **Date** |
| 692 Open | Paragraph 3.2.2.1.6 Ultimate Combined Loads. The mechanical external, thermally induced, and internal pressure loads shall be combined in a rational manner according to the equation given below to determine the design loads. Any other loads induced in the structure, e.g., during manufacturing, shall be combined in a rational manner. In no case shall the ratio of the allowable load to the combined limit loads be less than the factor in Paragraph 3.2.2.1.5.2. | SRM | Waiver: RSRM nozzle adhesive bondlines. Nozzle bondline analysis for EA946 and EA913NA adhesives does not explicitly include manufacturing residual stresses, accommodation is by increased safety factor | Test and analysis support conclusion that the nozzle will remain bonded prelaunch and through flight. Process and materials improvements have increased A-basis properties strength from 1500 psi to 2390 psi. Generally nozzle adhesive bonds are structurally fail-safe: phenolic rings mechanically interlocked and loaded in compression during motor operation. Primary structure (nozzle metal housings) meets 1.4 SF without including support of the adhesive bonds and phenolics. Multiple low probability events necessary to thermally fail nozzle due to gas flow between phenolics and housing. All 260 nozzles in SRM and RSRM program have met design requirement of thermally protecting housings. Residual stresses have been significantly reduced and bond line robustness increased through process control improvements. STS-109 (RSRM-83) and subsequent motor effectivities identified for this waiver are safe to fly | STS-107, STS-109 thru STS-118 | Space Shuttle PRCBDs S071796; S071796R1 | 2/22/2002; 10/9/2003 |

## Appendix C: Revised Historical Design Factors for NASA Space Vehicles

Table C-1. Historical design factors for NASA space vehicles. (*Revised from Table 3.2 in original report.*)

| HISTORIC DESIGN FACTORS FOR SPACE VEHICLES<br>Component | Factor | Apollo (NASA-MSC) | Gemini (NASA-MSC) | Mercury (NASA-MSC) | MOL (USAF) | DYNA SOAR (USAF) | Skylab S-IVB (NASA-MSFC) | Shuttle | Space Hab | ISSA SSP 30559 | S-IVB (NASA-MSFC) | S-II (NASA-JSFC) | S-I (NASA-MSFC) | Manned-General NASA-MSC | Manned-General NASA-MSFC | Manned-General AFSC-DH 3-26 | Airlock (MDAC - St. Louis) | Lunar Orbiter(Boeing) | Thor/Delta Thor/Agena (MDAC - Santa Monica) | Unmanned Spacecraft(Lockheed MSC) | Agena (Lockheed MSC) | Polaris(Lockheed MSC) | Scout(LTV Aerospace) | Atlas(GD/C) | Pioneer | Viking (MMC - JPL) | Titan III-C (MMC) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| General Structure | Yield | 1.1 * | 1.1 * | 1.1 * | 1.0 | † | 1.1 | -@ | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.15 | 1.0 | 1.0 | 1.0 | 1.0 | 1.15 | 1.0 | 1.0 | 1.0 | 1.0 |
| | Ultimate | 1.5 | 1.36 | 1.5 | 1.4 | 1.5 ‡ | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.36 | 1.5 | 1.25 | 1.25 | 1.25 | 1.25 | 1.5 | 1.25 | 1.5 | 1.25 | 1.25 |
| Tanks-Liquid Propellant and Other Fluids-Cryogenics | Yield | 1.33 | - | - | 1 | 1.5 | 1.1 | | | | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | | | | | | | | | | | | 1.0 |
| | Proof | 1.33 | 1.5 | 1.5 | 1.5 | 1.5 | 1.05 | | | | 1.1 | 1.05 | 1.1 | 1.1 | 1.05 | 1.5 | | | 1.05 | 1.67 | 1.1 | | | | | | 1.0 |
| | Ultimate | 1.5 | 2.0 | 2.0 | 2.0 | 1.33 x 1.5 | 1.4 | | | | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.33 x 1.5 | | 1.33 | 2.22 | 1.25 | | | 1.25 | | | 1.25 | |
| Propellant Lines | Yield | - | - | - | - | - | - | | | | | | | | | 1 | | | | | | | | | | | |
| | Proof | - | - | - | - | - | - | | | | | | | | | 1.5 | | | | | | | 1.5 | | | | |
| | Ultimate | - | - | - | - | - | - | | | | | | | | | 1.88 | | 1.65 | | | | | 2.5 | | | | |
| Vessels (High Pres Bottle) Vent Lines Plumbing, etc. | Yield | 1.33 | 1.0 | 1.0 | 1.0 | - | 1.1 | | | | 1.1 | 1.15 | 1.15 | 1.33 | 1.1 | | 1.0 | 1.5 | | | | | | 1.0 | | 2.25 | |
| | Proof | 1.33 | 1.67 | 1.7 | 1.5 | - | 1.1 | | | | 1.1 | 1.05 | 1.05 | 1.33 | 1.05 | | 1.67 | 2.0 | 1.33 | | | | | 1.67 | 1.66 | 2.0 | |
| | Ultimate | 1.5 | 2.22 | 2.2 | 2.0 | - | 4.0 | | | | 4.0 | 1.4 | 1.4 | 2.0 | 1.4 | | 2.22 | | 1.5 | | | | | 2.0 | 2.0 | 4.0 | |
| Pressurized Structure-Cabins, Airlocks, Ducts, etc. | Yield | 1.0 | 1.0 | 1.3 | 1.0 | 1.0 | - | - | 1.65 | 1.7 | | | | | | 1.1 | 1.0 | | | | | | | | | | |
| | Proof | NA | 1.33 | - | 1.33 | 1.2 | - | 1.1 | 1.5 | 1.5 | | | | | | | 1.36 | | | | | | | | | | |
| | Ultimate | 1.5 | 2.0 | 2.0 | 2.0 | 1.5 | - | 1.5 | 2.0 | 2.0 | | | | | | 1.4 | 2.0 | | | | | | | | | | |
| Hydraulic and Pneumatic Sys. (Incl. Lines, Fitting, Tubing) | Yield | - | 1.0 | 1.0 | 1.0 | | 1.1 | | | | 1.1 | | | | | 1.0 | 1.0 | 2.0 | | | | | 1.5 | | | 2.25 | 2.0 |
| | Proof | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | | | | 2.0 | 2.0 | | | | 2.0 | 2.0 | 2.0 | 2.5 | 2.0 | 1.5 | | 1.5 | | | 2.0 | 2.0 |
| | Ultimate | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | | | | 4.0 | 4.0 | | | | 4.0 | 4.0 | 4.0 | 5.0 | 4.0 | 3.0 | | 2.5 | | | 4.0 | 4.0 |
| Nonflight: Dangerous To Personnel | Yield | | | | 1.0 | | | | | | | | | | | 1.0 | | | 1.5 | | | | | | | 1.6 | |
| | Ultimate | | | | 1.5 | | | | | | | | | | | 1.5 | | | 4.0 | | | | | | | 2.0 | |
| Nonflight: Not Dangerous To Personnel | Yield | | | | 1.0 | | | | | | | | | | | 1.0 | | | 1.0 | 1.15 | | 1.15 | | | | | 1.0 |
| | Ultimate | | | | 1.25 | | | | | | | | | | | 1.25 | | | 1.33 | 1.50 | | 1.50 | | | | | 1.25 |
| Pneumatic and Hydraulic System Components Heat Exchangers (Including Cold Panels). Quick Disconnect, Blowers, Valves, Pressure Switches, Regulators | Yield | | 1.0 | 1.0 | 1.0 | | | | | | | | | | | | 1.0 | | | | | | | | | | 1.0 |
| | Proof | 1.33 | 1.5 | 1.5 | 1.5 | 1.5 | | | | | | | | | | | 1.5 | | | 1.5 | | | | | | | 1.5 |
| | Ultimate | 1.5 | 2.5 | 2.5 | 2.0 | 2.5 | | | | | | | | | | | 2.5 | | | 2.5 | | | | | | | 2.5 |

New values being quoted by Clarence (Tom) Modelin (retired JSC)

* 1.0

† 1.1

‡ 1.4

@ 1.1 on external tank and solid rocket boosters

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Following the Columbia Accident Investigation Board (CAIB) Report, the "Diaz Team" identified CAIB Report elements with Agency-wide applicability. The "Diaz Report", A Renewed Commitment To Excellence, generated an action to "Review current policies and waivers on safety factors". This document addresses this action.

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