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Operational Guidelines for Spaceflight Pressure Vessels

31 March 2005

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VOLPE NATIONAL TRANSPORTATION SYSTEMS CENTER
U.S. DEPARTMENT OF TRANSPORTATION
Cambridge, Massachusetts

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16. Abstract

The Aerospace Corporation (Aerospace) was tasked by the Volpe National Transportation Systems Center to provide technical support to the Federal Aviation Administration, Office of Commercial Space Transportation (FAA/AST), to develop operational guidelines for the recurring use of safety-critical pressure vessels (PVs) in spaceflight systems. Emphasis was on PV guidelines to help ensure the safety of flight crew and passengers on commercial reusable launch vehicles (RLVs).

These guidelines were developed by reviewing and analyzing specifications, requirements, and lessons-learned for safety of PVs used in commercial, military, and experimental space systems, and past and present human-carrying space systems, followed by interpolation and projection of these requirements for crew and passengers aboard both suborbital and orbital categories of future commercial RLVs.

These guidelines appear to be robust, reasonable, and adaptable for PVs used in various RLV configurations. They do not appear to impose unreasonable technical or economic barriers to advancement of the commercial pressure vessel industry.

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Abstract

The Aerospace Corporation (Aerospace) was tasked by the Volpe National Transportation Systems Center to provide technical support to the Federal Aviation Administration, Office of Commercial Space Transportation (FAA/AST), to develop operational guidelines for the recurring use of safety-critical pressure vessels (PVs) in spaceflight systems. Emphasis was on PV guidelines to help ensure the safety of flight crew and passengers on commercial reusable launch vehicles (RLVs).

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These guidelines appear to be robust, reasonable, and adaptable for PVs used in various RLV configurations. They do not appear to impose unreasonable technical or economic barriers to advancement of the commercial pressure vessel industry.

Foreword

This document presents the results of a Volpe National Transportation Systems Center funded task, Operational Guidelines for Spaceflight Pressure Vessels, carried out by The Aerospace Corporation. Mr. James B. Chang and Mr. Robert W. Seibold served as the Principal Investigator and Program Manager, respectively. The purpose of this task was to recommend suitable requirements applicable for the recurring use of safety-critical pressure vessels in reusable launch vehicles and to provide guidelines for implementation of these requirements.

Most of the recommended requirements are based on two American National Standards Institute (ANSI)/American Institute of Aeronautics and Astronautics (AIAA) documents, ANSI/AIAA S-080 and S-81, for metallic pressure vessels (MPVs) and composite overwrapped pressure vessels (COPVs), respectively. Some of the guidelines applicable to COPVs were taken from an Aerospace Corporation Technical Report, TR-2003(8504)-1, "Implementation Guidelines for ANSI/AIAA S-081: Space Systems Composite Overwrapped Pressure Vessels."

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Executive Summary

Introduction and Objective

The Aerospace Corporation (Aerospace) was tasked by the Volpe National Transportation Systems Center to provide technical support to the Federal Aviation Administration, Office of Commercial Space Transportation (FAA/AST), to develop operational guidelines for the recurring use of safety-critical pressure vessels (PVs) in spaceflight systems. Emphasis was on PV guidelines to help ensure the safety of flight crew and passengers on commercial reusable launch vehicles (RLVs). Aerospace is pleased to submit this final report, in accordance with the requirements delineated in Section F, Deliveries or Performance, of Contract No. DTRS57-99-D-00062, Task 7.0.

Scope and Purpose

This document presents proposed requirements applicable to metallic pressure vessels (MPVs) and metal-lined composite overwrapped pressure vessels (COPVs) used in RLVs. This document also provides guidelines for implementing these requirements. Requirements recommended herein apply primarily to the safety of the ground and flight crew as well as passengers in RLVs. However, important mission reliability related requirements are also included.

Recommended Key Requirements and Implementation Guidelines for MPVs

In the design, analysis, test, inspection, operation and maintenance of MPVs used in RLVs, the following are essential elements that must be addressed to assure safety of crew and passengers:

- System Analysis
- Strength
- Fracture Control
- Leak-Before-Burst (LBB) Failure Mode
- Fatigue (Safe-Life)
- Damage Tolerance
- Inspection
- Proof Tests
- Qualification Tests
- Operation and Maintenance
- Repair and Refurbishment

Recommended requirements associated with the above-listed elements are presented herein. The majority of the recommended requirements are derived based on ANSI/AIAA S-080 (defined in Section 2.0). Guidelines on how to implement these requirements are also presented.

Recommended Key Requirements and Implementation Guidelines for COPVs

With the following exceptions, the above requirements for MPVs are also applicable to COPVs:

- Composite Material Strength Design Allowable
- Stress Rupture Life
- Impact Damage Control

The majority of the recommended requirements for COPVs are derived based on ANSI/AIAA S-081 (defined in Section 2.0). Details of the COPV-specific requirements are presented herein.

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1. Scope and Purpose

1.1 Scope

This document presents proposed requirements applicable to metallic pressure vessels (MPVs) and metal-lined composite overwrapped pressure vessels (COPVs) used in reusable launch vehicles (RLVs). This document also provides guidelines for implementing these requirements.

1.2 Purpose

Requirements recommended herein apply primarily to the safety of the ground and flight crew as well as passengers in RLVs. However, important mission reliability–related requirements are also included.

2. Key Reference Documents

ANSI/AIAA S-080-1998, Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components, September 13, 1999.

ANSI/AIAA S-081-2000, Space Systems – Composite Overwrapped Pressure Vessels (COPVs), December 19, 2000.

ASME Boiler and Pressure Vessel Codes, Sections VIII and X.

MIL-STD-1522A, Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems, United States Air Force, 1984.

MIL-STD-1540C, Test Requirements for Launch, Upper-Stage and Space Vehicles, 1994.

3. Vocabulary

3.1 Definitions

The following definitions of significant terms are provided to ensure precision of meaning and consistency of usage. When in conflict with the definition of a specific standard, the one defined in the respective standard holds.

A-Basis Allowable: The mechanical strength values such that 99% of the population will meet or exceed the specified values with a confidence level of 95%.

Acceptance Tests: The required formal tests conducted on flight hardware to ascertain that the materials, manufacturing processes, and workmanship meet specifications and that the hardware is acceptable for its intended use.

Allowable Load (Stress): The maximum load (stress) that can be accommodated by a structure (material) without rupture, collapse, or detrimental deformation in a given environment. Allowable loads (stresses) commonly correspond to the statistically based minimum ultimate strength, buckling strength, and yield strength, as applicable.

Autofrettage/Sizing: The manufacturing process to which a metal-lined COPV is experienced with the intent of yielding the liner or portion of the liner.

Burst Factor (BF): A multiplying factor applied to the Maximum Expected Operating Pressure (MEOP) to obtain the design burst pressure.

Composite Overwrapped Pressure Vessel (COPV): A pressure vessel with a composite shell fully or partially encapsulating a metallic liner. The liner serves as a fluid (gas or liquid) permeation barrier and may or may not carry substantive pressure loads. The composite shell generally carries pressure and environmental loads. In this standard, a COPV with a metallic liner is referred to as a metal-lined COPV.

Composite Overwrap: The composite structural part of a COPV, which is usually in the form of spherical shell, cylindrical shell, or a body of revolution.

Damage Tolerance: The ability of a PV to resist failure due to the presence of flaws, cracks, or other damage for a specified period of unrepaired use.

Damage-Tolerance Life: The required period of time or number of cycles that the MPV or the metal liner of a COPV, containing the largest undetected crack shown by analysis or testing, will not leak or fail catastrophically in the expected service load and environment. This term is also referred to as safe-life in certain documents.

Design Burst Pressure: The pressure that a pressure vessel must withstand without rupture in the applicable operating environment. It is equal to the product of the MEOP and a burst factor.

Design Safety Factor: A multiplying factor applied to the limit load and/or MEOP for the purpose of analytical assessment and/or test verification of structural adequacy.

Design Ultimate Load: The product of the design ultimate safety factor and the limit load. It is the load that the structure must withstand without rupture or collapse in the expected operating environment.

Destabilizing Pressure: A differential pressure that produces a compressive stress in a pressure vessel that causes buckling.

Detrimental Deformation: The detrimental deformation, deflection, or displacement that prevents any portion of the pressure vessel from performing its intended function or that reduces the probability of successful completion of the mission.

Development Test: A test that is conducted by the manufacturer in order to provide design information used to check the validity of analytic techniques and assumed design parameters; to uncover unexpected system response characteristics; to evaluate design changes; to determine interface compatibility; to prove qualification and acceptance procedures and techniques; to establish accept/reject criteria for nondestructive inspection/nondestructive evaluation (NDI/NDE); or any other purpose necessary to establish the validity of the design and manufacturing processes.

Dynamic Envelope: The space or volume allocated to a component, which includes allowance for all displacements and deflections associated with the limit load.

Environments: The environmental exposures (such as humidity, temperature, vibration, acoustic, and radiation levels) to which the pressure vessel is subjected after completion of manufacture and final inspection.

Elastically Responding Regions: A region of the metal liner of a COPV that responds elastically during pressurization at all pressures up to and including the acceptance proof pressure.

Fatigue: The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks, or complete fracture after a sufficient number of fluctuations (cycles).

Fatigue Life: The number of cycles of applied external loads and/or pressurization that the unflawed PV can sustain before failure of a specified nature could occur.

Flaw: A local discontinuity in a structural material such as a scratch, notch, crack, or void.

Flaw Shape (a/2c or a/c): The shape of a surface flaw, or a corner flaw, where "a" is the depth and "2c" or "c" is the length of the flaw.

Ground Maximum Operating Pressure: The maximum pressure to which a PV will be pressurized after loading with a specified fluid as part of the vehicle ground processing pre-launch checkout.

Hazard: An existing or potential condition that may result in a mishap.

Hazardous Fluid/Material: A liquid or gas that may be toxic, reactive, or flammable either by itself or in combination with other materials.

Impact Damage: An induced fault in a COPV caused by an object strike on the vessel or vessel strike on an object.

Leak-Before-Burst (LBB) Design: A design approach within which, at the maximum expected operating pressure (MEOP), potentially pre-existing flaws in the liner, should they grow, will grow through the liner thickness and will result in pressure-relieving leakage rather than burst or rupture.

Limit Load: The maximum expected external load or worst-case combination of loads, which a structure may experience during the performance of specified missions in specified environments. When a statistical estimate is applicable, the limit load is that load not expected to be exceeded at 99% probability with 90% confidence.

Liner: A metallic or plastic component of a COPV upon which the composite material is applied. In this document, the liner includes all bosses.

Loading Spectrum: A representation of the cumulative loading anticipated for the pressure vessel under all expected operating environments. Significant transportation and handling loads are included.

Margin of Safety (MoS):

$$MoS = \frac{\text{Allowable Load}}{\text{Limit Load} \times \text{Design Safety Factor}} - 1$$

Note: Load may mean stress or strain.

Maximum Design Pressure (MDP): The highest possible operating pressure considering maximum temperature, maximum relief pressures, maximum regulator pressure, and, where applicable, transient pressures excursions. (MDP for Space Shuttle 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.

Maximum Expected Operating Pressure (MEOP): The maximum pressure that a pressure vessel is expected to experience during its service life in association with its applicable operating environments.

Mechanical Damage: An induced fault in the composite overwrap of a COPV, which is caused by the surface abrasion, cut or impact.

Mechanical Damage Control Plan: A plan that defines the mechanical damage threats to a COPV during manufacturing, integration, transportation, and incorporation into a space system up to the time of launch and the steps taken to minimize the possibility of damage due to these threats.

Metal-Lined COPV: A COPV that has a metal liner.

Plastically Responding Regions of the Liner: A region of the liner that experiences plastic response at MEOP.

Pressure Vessel: A container designed primarily for the storage of pressurized fluids which (1) contains stored energy of 14,240 foot pounds (19,310 joules) or greater, based on adiabatic expansion of a perfect gas, or (2) contains gas or liquid which will create a mishap (accident) if released, or (3) will experience a MEOP greater than 100 psi (700 kPa).

Procurement Agency: The organization that places a manufacturer on contract to design, qualify, test, and fabricate the pressure vessel.

Qualification Tests: The required formal contractual tests used to demonstrate that the design, manufacturing, and assembly have resulted in a design that conforms to specification requirements.

Residual Strength: The maximum value of nominal load (stress) that a cracked or damaged structure is capable of sustaining without failure.

Residual Stress: The stress that remains in a pressure vessel after processing, autofrettage, fabrication, assembly, testing, or operation; for example, welding induced residual stress.

Safe-Life: In this document, safe-life and damage-tolerance life are interchangeable terms.

Service Life: The period of time or number of cycles that begins with completion of physical assembly or acceptance testing, with associated determination of the state or nature of pre-existing flaws based on NDI or flaw-screening proof test, and continues through all subsequent exposure to environments, including as applicable, handling, storage, transportation, service, refurbishment, re-testing, reentry or recovery from orbit, and reuse. For cases where a launch-site pressure test will be performed, the service life includes this pressure cycle.

Stress-Corrosion Cracking: A mechanical-environmental induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw in a metallic pressure vessel or the metallic part of a COPV.

Stress Intensity Factor (*K*): A parameter that characterizes the stress-strain behavior at the tip of a crack contained in a linear elastic, homogeneous, and isotropic body.

Stress Ratio: The calculated or measured stress in the fiber at MEOP divided by the ultimate delivered strength of the fiber, as calculated, or measured from COPV burst tests,

Stress Rupture Life: The minimum time during which the composite structure maintains structural integrity considering the combined effects of stress level(s), time at stress level(s), and associated environments.

Visual Damage Threshold (VDT): An impact energy level shown by test(s) that creates an indication on the composite shell of a COPV that is (barely) detectable by a trained inspector using an unaided visual technique. (It is noted that no quantitative reliability or confidence level is associated with this technique.)

3.2 Abbreviations and Acronyms

AE	Acoustic Emission
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ASIP	Aircraft Structural Integrity Program
ASME	American Society of Mechanical Engineers
ASSIST	Acquisition Streamlining and Standardization Information System
AST	Office of Commercial Space Transportation
BAI	Burst Strength After Impact
CFRs	Code of Federal Regulations
COPV	Composite Overwrapped Pressure Vessel
COTR	Contracting Officer's Technical Representative
CPV	Composite Pressure Vessel
DBF	Design Burst Factor
DOD	Department of Defense
DSF	Design Safety Factor
EDM	Electric Discharge Machining
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FCP	Fracture Control Plan
FEA	Finite Element Analysis
$\mathbf{F_{tu}}$	Ultimate Tensile Strength
G	Unit of force: acceleration equivalent to gravitational force at rest
Gr/Ep	Graphite/Epoxy
HAZ	Heat Affected Zone
Hz	Hertz
HZ	Hydrazine
IAW	In Accordance With
ICP	Impact Damage Control Plan

IDP	Impact Damage Threshold
IMIT	Instrumented Mechanical Impact Tester
JSSG	Joint Service Specification Guide
K	Stress intensity factor
K_c	Fracture Toughness
K_I	Applied stress intensity factor
K_{TH}	Threshold stress intensity factor
LBB	Leak-Before-Burst
LEFM	Linear Elastic Fracture Mechanics
LOX	Liquid Oxygen
MCPT	Multiple-Cycle Proof Test
MDP	Maximum Design Pressure
MEOP	Maximum Expected Operating Pressure
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MPS	Metallic Pressurized Structure
MPV	Metallic Pressure Vessel
MRB	Material Review Board
MS	Margin of Safety
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
PAN	Polyacrylonitrile
PoD	Probability of Detection
PoS	Probability of Survival
psig	Pounds per square inch, gauge
PTC	Part-through Crack
PV	Pressure Vessel
QA	Quality Assurance
RLV	Reusable Launch Vehicle
RMS	Root Mean Square
RTCA	Radio Technical Commission for Aeronautics
RTD&E	Research, Development, Test & Evaluation
SCC	Standard Cubic Centimeter
Sec	Second
USAF/SMC	United States Air Force / Space and Missile Systems Center
VC	Knots Calibrated Airspeed
VDT	Visual Damage Threshold

4. Introduction

4.1 Historical Background

PVs such as helium gas bottles and hydrazine propellant tanks are some of the most safety-critical components used in space systems. Any PV that contains compressed gas constitutes a potential hazard because of the risk of inadvertent release of the stored energy. If a high-pressure gas bottle bursts, the stored energy can be converted to a destructive blast wave that can destroy surrounding structures or cause severe injuries or fatalities to personnel around it. Furthermore, a leaking helium gas bottle may jeopardize the planned mission of any space system. A leaking liquid propellant storage tank is equally dangerous because many propellants present toxicity hazards to ground personnel during handling and installation and operation.

Most PVs used in earlier space systems were made of high-strength metals such as steel, titanium, and Inconel alloys. They are referred to as metallic pressure vessels (MPVs). In the 1970s, all spaceflight MPVs used in military space systems were designed, analyzed, and qualified per MIL-STD-1522 (Ref. 1). In 1984, MIL-STD-1522 was revised to include safe-life demonstration requirements for MPVs that contain hazardous fluids or exhibit brittle fracture failure mode. The revised version was identified as MIL-STD-1522A and was the most popular PV standard used in the space industry on military, civil, domestic, and foreign space programs in the last two decades. However, there were a few important areas that were not covered in MIL-STD-1522A. The major ones include: no detailed requirements for composite materials used in composite overwrapped pressure vessels (COPVs); no specific requirements for metallic pressurized structures such as the main propellant tanks of a launch vehicle; and no distinction for special pressure equipment including batteries, heat pipes, sealed containers, and cryostats (Ref. 2).

In 1993, Aerospace was tasked by Air Force (AF)/Space and Missile Systems Center (SMC) to update MIL-STD-1522A to include specific requirements in those areas. However, due to the military acquisition reform, SMC cancelled most of the military standards and specifications and discontinued the update activity. Recognizing the need to have industry uniform standards, in 1996, the American Institute of Aeronautics and Astronautics (AIAA) formed the Aerospace Pressure Vessel Standard Working Group to take over the standard development activities for pressure vessels and related hardware items. All standards developed by this group are to be approved by the American National Standard Institute (ANSI) as American national standards. The first standard developed by this working group was ANSI/AIAA S-080-1998, which contains the requirements for MPVs and other metallic pressurized hardware items. Specific requirements for metallic pressurized structures, battery cases, heat pipes, etc., are contained in this standard.

The second standard developed by this working group was the COPV standard, ANSI/AIAA S-081-2000. Currently, high-pressure helium gas storage bottles used in the launch vehicles, upper-stage vehicles and spacecraft used for military and commercial space programs are fabricated from carbon-epoxy composite materials overwrapping metal liners such as aluminum alloy. Carbon-epoxy composite materials are also being widely used for fabricating aircraft structures including wings and tails and launch vehicle structures such as solid rocket motor cases and fairings. These structures exploit the high specific strength and modulus of carbon fibers. However, carbon-epoxy composites are susceptible to impact damage. Damage tolerance control requirements have been imposed on critical-to-flight composite aircraft structures (Ref. 3). But requirements established for aircraft structures cannot be directly applied to COPVs because of their sizes and loading conditions.

In order to assess the need for impact damage control and other requirements on spaceflight COPVs, AF/SMC and the National Aeronautics and Space Administration (NASA) sponsored a research, development, test and evaluation (RDT&E) program, "Enhanced Technology for Composite Overwrapped Pressure Vessels," which was initiated in 1995 (Ref. 4). An impact damage effects study on COPVs was the major task of this RDT&E effort. Test results obtained in this program showed that thin-wall COPVs (wall thickness less than 0.25 in.) are indeed vulnerable to impact. At impact damage energy levels even less than the COPV's visible damage threshold (VDT), the residual strength, or burst strength after impact (BAI), for a batch of flight-qualified lightweight cylindrical COPV material (0.15 in. wall thickness) displayed up to 30 percent reduction. One such COPV that was fully charged with helium gas exploded on the test stand 0.7 sec. after impact (Ref. 5). The findings from the impact damage effects study motivated the introduction of a new set of impact damage control requirements for thin-walled lightweight COPVs in S-081. In addition to impact damage control requirements, S-081 contains many new requirements including leak-before-burst (LBB) and safe-life test requirements for elastic-plastic liners and strength allowables and stress-rupture data generation requirements for composite materials.

4.2 Recommended Requirements for PVs Used in RLVs

Most of the requirements specified in S-080 and S-081 are for both single-mission and multimission applications. These requirements are therefore also applicable for RLVs. However, there are some special requirements, particularly those related to damage tolerance, that should be imposed on PVs used in RLVs. These special requirements and other general requirements are presented in Sections 6 and 7 for MPVs and COPVs, respectively.

4.3 Implementation Guidelines

All the requirements contained in S-080, S-081, and other standards are "what-to-do" in nature. For some of the "new players" who are just beginning to engage in the design, testing, operation and maintenance of PVs, it is prudent to create a "how-to" document that provides implementation guidelines. This is particularly true for COPV developers and users. For this reason, The Aerospace Corporation published technical report TR-2003(8504)-1 (Ref. 6) to provide guidelines for the implementation of some of the unique requirements specified in S-081. Those items applicable to RLVs are documented in the present guidelines document.

5. Current Practices and Requirements

As illustrated in Figure 5-1, numerous documents were perused to develop general design guidelines, considerations, practices, and verification criteria for spaceflight pressure vessels.

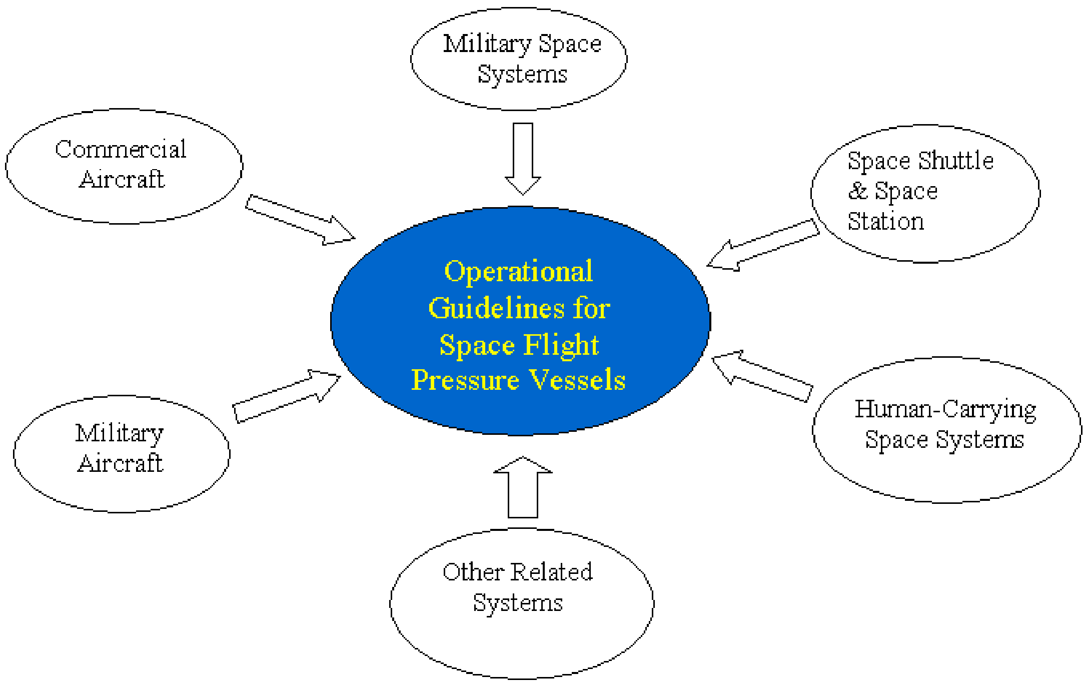


Figure 5-1. Approach to develop operational guidelines for spaceflight pressure vessels.

Design practices in place for aircraft and space systems are discussed in Sections 5.1 through 5.3.

5.1 Aeronautical Systems

The Federal Aviation Regulations (FARs) are found in Title 14, Chapter 1, of the Code of Federal Regulations (CFRs) and provide the regulatory framework for general aviation and commercial aircraft. The FARs are based on fail-safe design concepts that have evolved over a period of years. The "Airworthiness Standards" for various category aircraft are addressed in 14 CFR parts 23, 25, 27, and 29, and are categorized as follows:

- Part 23: Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
- Part 25: Airworthiness Standards: Transport Category Airplanes
- Part 27: Airworthiness Standards: Normal Category Rotorcraft
- Part 29: Airworthiness Standards: Transport Category Rotorcraft

Each of these Parts includes Subparts categorized as follows:

- Subpart A: General
- Subpart B: Flight
- Subpart C: Structure (designated "Strength Requirements" for parts 27 and 29)

- Subpart D: Design and Construction
- Subpart E: Powerplant
- Subpart F: Equipment
- Subpart G: Operating Limitations and Information

In addition to the FARs, concomitant Advisory Circulars also play an important role in the process of ensuring public and passenger safety, as they provide various acceptable means of showing compliance with the requirements of the FARs. The principal Advisory Circulars addressing safety of airplane systems are AC 23.1309 1-3, Equipment, Systems, and Installations in Part 23 Airplanes, and AC 25.1309-1A, System Design and Analysis.

5.1.1 Aeronautical Systems—Commercial Practices

Manufacturers of PVs for aeronautical systems rely on proprietary specifications from aircraft manufacturers to establish requirements for PVs (e.g., gas bottles and water tanks) used on fixed-wing and rotary-wing aircraft. These specifications establish requirements on factors of safety, fatigue life, safe life, qualification test, acceptance test, and recertification test.

The primary source for design requirements is ASME Section 10 for common pressures and ASME Section 8 for higher pressures. A secondary source is Radio Technical Commission for Aeronautics (RTCA) document D0160. Typical PV requirements are discussed below:

- For water tanks, the proof-pressure is generally 2.5 × working pressure. Burst is double the proof-pressure, i.e., 5 × working pressure.
- Pressure limits for connections are generally 2.5 × working pressure.
- Humidity requirements are drawn from MIL-STD-810 and flammability requirements from 14 CFR, part 25. Chemical resistance requirements are specific to where the item is placed, e.g., near Skydrol hydraulic fluid.

The aircraft manufacturers are generally very strict about any changes made by the PV manufacturers. Any change requires recertification and retesting. This is accomplished by exercising engineering judgment followed by a battery of tests.

5.1.2 MPVs Used in the Hydraulic System

Federal Regulation 14 CFR part 25 specifies requirements for MPVs used in hydraulic systems as follows:

(a) Design:

(1) Each element of the hydraulic system must be designed to withstand, without deformation that would prevent it from performing its intended function, the design operating pressure loads in combination with limit structural loads that may be imposed.

(2) Each element of the hydraulic system must be able to withstand, without rupture, the design operating pressure loads multiplied by a factor of 1.5 in combination with ultimate structural loads that can reasonably occur simultaneously. Design operating pressure is maximum normal operating pressure, excluding transient pressure.

(b) Tests and analysis:

(1) A complete hydraulic system must be static tested to show that it can withstand 1.5 times the design operating pressure without a deformation of any part of the system that would prevent it from performing its intended function. Clearance between structural members and hydraulic system elements must be adequate, and there must be no permanent detrimental deformation. For the purpose of this test, the pressure relief valve may be made inoperable to permit application of the required pressure.

(2) Compliance with Sec. 25.1309 for hydraulic systems must be shown by functional tests, endurance tests, and analyses. The entire system, or appropriate subsystems, must be tested in an airplane or in a mock-up installation to determine proper performance and proper relation to other aircraft systems. The functional tests must include simulation of hydraulic system failure conditions. Endurance tests must simulate the repeated complete flights that could be expected to occur in service. Elements that fail during the tests must be modified in order to have the design deficiency corrected and, where necessary, must be sufficiently retested. Simulation of operating and environmental conditions must be completed on elements and appropriate portions of the hydraulic system to the extent necessary to evaluate the environmental effects. Compliance with Sec. 25.1309 must take into account the following:

(i) Static and dynamic loads, including flight, ground, pilot, hydrostatic, inertial and thermally induced loads, and combinations thereof,

(ii) Motion, vibration, pressure transients, and fatigue,

(iii) Abrasion, corrosion, and erosion,

(iv) Fluid and material compatibility, and

(v) Leakage and wear.

(c) Fire protection: Each hydraulic system using flammable hydraulic fluid must meet the applicable requirements of Secs. 25.863, 25.1183, 25.1185, and 25.1189.

5.1.3 MPVs Used in Pressurization and Pneumatic Systems

Federal Regulation 14 CFR part 25 specifies requirements for MPVs used in pressurization and pneumatic systems as follows:

(a) Pressurization system elements must be burst pressure tested to 2.0 times, and proof pressure tested to 1.5 times, the maximum normal operating pressure.

(b) Pneumatic system elements must be burst pressure tested to 3.0 times, and proof pressure tested to 1.5 times, the maximum normal operating pressure.

(c) An analysis, or a combination of analysis and test, may be substituted for any test required by paragraph (a) or (b) of this section if the Administrator finds it equivalent to the required test.

(d) Damage-tolerance evaluation. The evaluation must include a determination of the probable locations and modes of damage due to fatigue, corrosion, or accidental damage. The determination must be by analysis supported by test evidence and (if available) service experience. Damage at multiple sites due to prior fatigue exposure must be included where the design is such that this type of damage can be expected to occur. The evaluation must incorporate repeated load and static analyses supported by test evidence.

(e) The extent of damage for residual strength evaluation at any time within the operational life must be consistent with the initial ability for its detection and its subsequent growth under repeated loads. The residual strength evaluation must show that the remaining structure is able to withstand loads (considered as static ultimate loads) corresponding to the following conditions:

   (1) The limit symmetrical maneuvering conditions specified in Sec. 25.337 at Knots Calibrated Airspeed (VC) and in Sec. 25.345.

   (2) The limit gust conditions specified in Sec. 25.341 at the specified speeds up to VC and in Sec. 25.345.

   (3) The limit rolling conditions specified in Sec. 25.349 and the limit unsymmetrical conditions specified in Secs. 25.367 and 25.427 (a) through (c), at speeds up to VC.

   (4) The limit yaw maneuvering conditions specified in Sec. 25.351(a) at the specified speeds up to VC.

   (5) For pressurized cabins, the following conditions:

      (i) The normal operating differential pressure combined with the expected external aerodynamic pressures applied simultaneously with the flight loading conditions specified in paragraphs (d) (1) through (4) of this section, if they have a significant effect.

      (ii) The expected external aerodynamic pressures in 1 g flight combined with a cabin differential pressure equal to 1.1 times the normal operating differential pressure without any other load.

   If significant changes in structural stiffness or geometry, or both, follow from a structural failure, or partial failure, the effect on damage tolerance must be further investigated.

(f) Fatigue (safe-life) evaluation. Compliance with the damage-tolerance requirements of paragraph (d) of this section is not required if the applicant establishes that their application for a particular structure is impractical. This structure must be shown by analysis, supported by test evidence, to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks. Appropriate safe-life scatter factors must be applied.

5.2 Space Systems

Many existing MPVs and COPVs used in current civil and commercial space systems were designed, fabricated, tested and verified in accordance with the requirements set forth in a military standard, MIL-STD-1522A, issued in 1984, with some modifications. This section presents highlights of the requirements specified in MIL-STD-1522A.

5.2.1 MPVs

MPVs can be designed to satisfy ASME Pressure Vessel Code, Section VIII, or DOT Title 49. For those vessels not designed to the ASME Code or DOT Title 49, one of the two alternative approaches for their design, analysis and verification should be selected, as illustrated in Figure 5-2. Selection of the approach to be used is dependent on the desired efficiency of design coupled with the level of analysis and verification testing required. Two distinct verification paths must be satisfied if Approach A is selected: 1) Nonhazardous LBB with leakage of the contents not creating a condition that could lead to a mishap; and 2) Non-LBB in which failure can cause injury or fatalities due to blast wave and fragmentation, or Hazardous LBB, which causes a hazard if the pressure vessel leaks.

The specific design requirements for pressure vessels that select Approach A and Approach B are presented in Sections 5.2.1.1 and 5.2.1.2, respectively.

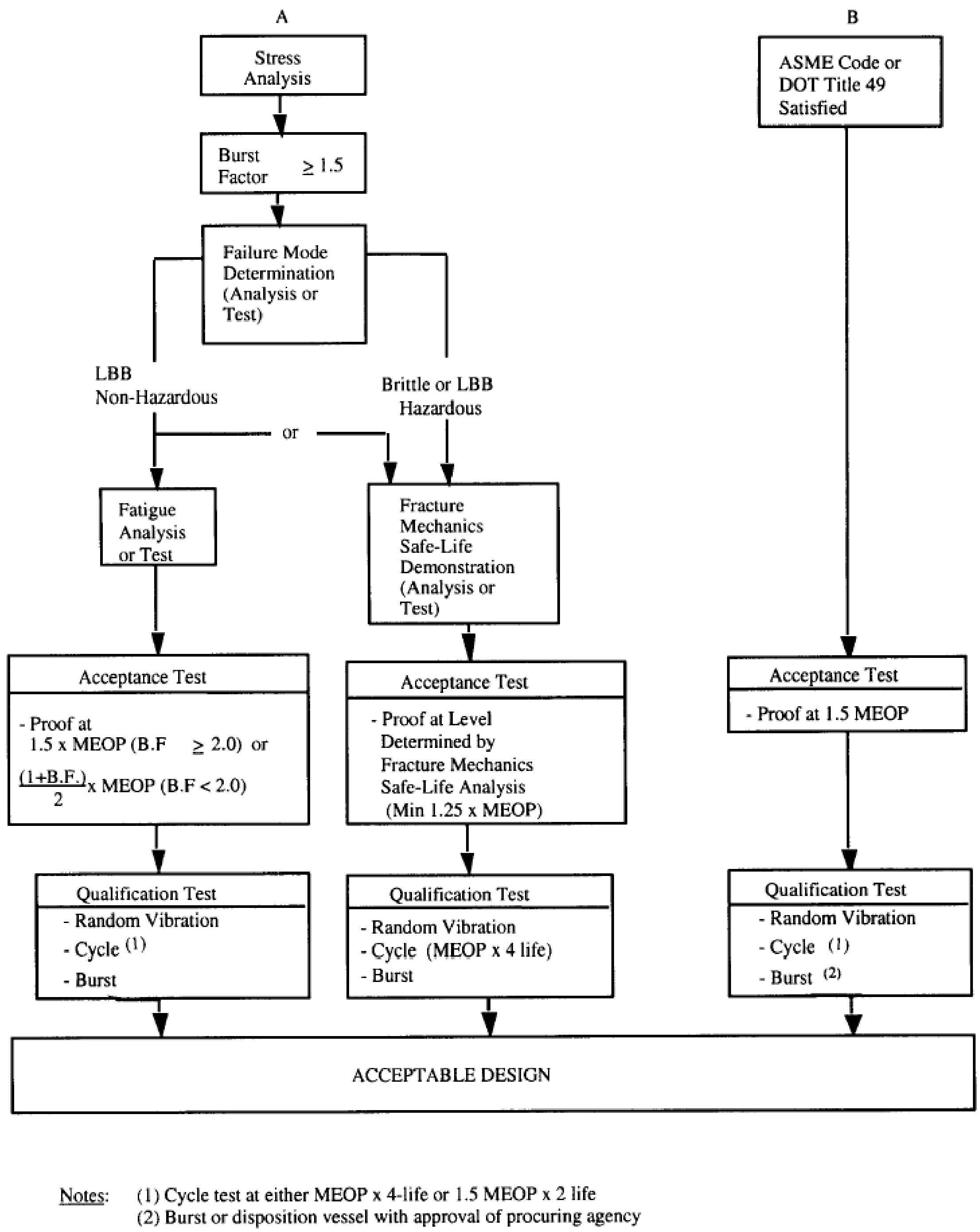


Figure 5-2. Pressure vessel design verification approach: qualification test.

5.2.1.1 MPVs with Nonhazardous LBB Failure Mode

MPVs containing nonhazardous fluid and exhibiting a leak-before-burst (LBB) failure mode may select the left-hand path of Approach A for design verification. The LBB failure mode should be demonstrated analytically or by test showing that an initial flaw of any size, considering a flaw shape range of $0.05 \leq a/2c \leq 0.5$, will propagate through the thickness of the pressure vessel before becoming critical.

5.2.1.1.1 Factor of Safety Requirement

The minimum design burst factor (DBF) should be 1.5.

5.2.1.1.2 Safe-Life Requirement

Conventional fatigue-life analysis should be performed, as appropriate, on the unflawed MPV to demonstrate its safe-life. The required safe-life is 4 × service life. When Minor's rule is employed, the following relationship should be satisfied:

$$\sum n_i / N_i \leq 0.8, \text{ where } n_i = 4 \text{ times the number of cycles applied at stress level i.}$$

5.2.1.1.3 Qualification Test Requirements

Qualification testing should be conducted on flight quality vessels. The test program should include LBB demonstration testing, fatigue life cycle testing, random vibration testing and burst testing. The flowing briefly describe the required tests:

- LBB Testing

  The test may be conducted on coupons that duplicate the materials (parent material, weldment, and heat-affected zone) and thicknesses of the pressure vessel, or on a PV representative of the flight hardware. Test specimens should be pre-flawed and cycled through the design spectrum to demonstrate stable flaw growth completely through the wall thickness. A sufficient number of tests should be conducted to establish that all areas (thicknesses) and stress fields will exhibit a LBB mode of failure.

- Pressure Testing

  Required pressure testing levels are shown in Table 5-1. Requirements for application of external loads in combination with internal pressures during testing must be evaluated based on the relative magnitude and/or destabilizing effect of stresses due to the external loads. If limit combined tensile stresses are enveloped by these pressure stresses, the application of external loads is not required. If the application of external loads is required, the load should be cycled to limit for four times the predicted number of operating cycles of the most design condition.

- Random Vibration Testing

  Random vibration testing should be performed per requirements of MIL-STD-1540 or equivalent standards unless it can be shown that the vibration requirement is enveloped by other qualification testing performed.

5.2.1.1.4 Acceptance Test Requirements

Acceptance tests should be conducted on every MPV before commitment to flight. The following are required as a minimum:

(a) Nondestructive Inspection. A complete inspection by the selected nondestructive inspection (NDI) technique(s) should be performed prior to proof pressure test.

(b) Proof Pressure Test. The required proof-pressure level should be equal to:

$$P_{proof} = [(1 + \text{Burst Factor})/2] \times (\text{MEOP}) \quad \text{or}$$
$$= 1.5 \times (\text{MEOP}), \text{ whichever is lower.}$$

Table 5-1. Qualification Pressure Testing Requirements

Test Item	No-Yield After:	No Burst[(1)] at:
Vessel #1[(2)]	-------	Burst Factor × MEOP
Vessel #2	Cycle at 1.5 × MEOP for 2× predicted number of operating cycles (50 cycles minimum). Cycle at 1.0 × MEOP for 4× predicted number of operating cycles (50 cycles minimum).	Burst Factor × MEOP

Notes:
(1) After demonstrating no-burst at the defined test level, increase pressure to actual burst of vessel. Record actual burst pressure.
(2) Test may be deleted at discretion of procuring agency.

5.2.1.1.5 Recertification Test Requirements

All refurbished MPVs should be recertified after each refurbishment to meet the acceptance test requirements for new pressure vessels to verify their structural integrity and establish their suitability for continued service before commitment to flight. MPVs that have exceeded the approved storage environment (temperature, humidity, time, etc.) should also be recertified to meet acceptance test requirements for new MPVs.

5.2.1.2 MPVs with Non-LBB or Hazardous LBB Failure Mode

5.2.1.2.1 Factor of Safety Requirements

Safe-life design methodology based on fracture mechanics techniques should be used to establish the appropriate design factor of safety and the associated proof factor for MPVs that exhibit brittle fracture or hazardous LBB failure mode. Unless otherwise specified, the minimum burst factor should be 1.5.

5.2.1.2.2 Safe-Life Requirements

Fracture mechanics crack growth analysis should be performed to demonstrate that the MPV has adequate safe-life. To perform fracture mechanics safe-life analysis, it should be assumed that flaws preexist in the most critical locations and load orientations. The initial flaw sizes should be defined by NDI or acceptance proof test. Nominal values of fracture toughness and crack-growth rate data associated with each alloy system, temper, product form, thermal and chemical environments, and loading spectra should be used along with a life factor of four (4) on specified service life in all safe-life analyses.

MPVs that experience sustained stress should also show that the corresponding applied stress intensity factor (K_I) during operation is less than the threshold stress intensity factor (K_{TH}) in the appropriate environment, i.e., $K_{TH} > K_I$.

Crack growth testing can be used to demonstrate fracture mechanics safe-life. Test specimens should contain prefabricated flaws with the initial sizes defined by NDI or proof test. Safe-life is considered demonstrated when the preflawed test specimens successfully sustain the limit loads and pressures in the expected operating environments for four (4) times the service life without rupture.

5.2.1.2.3 Qualification Test Requirements

The qualification test requirements specified in Section 5.2.1.1.3 should be met.

5.2.1.2.4 Acceptance Test Requirements

The acceptance test requirements specified in Section 5.2.1.1.4 should be met, except that the test levels should be determined by fracture mechanics analysis. The proof-pressure test can be conducted at cryogenic temperature if deemed necessary for the purpose of screening flaws.

5.2.1.2.5 Recertification Test Requirements

Requirements of Section 5.2.1.1.5 should be met.

5.2.1.3 MPVs Designed Employing ASME Boiler Code or DoT Title 49

MPVs designed and manufactured per the rules of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2, or DoT Title 49 do not need to meet the damage-tolerance life demonstration requirements.

5.2.1.3.1 Qualification Test Requirements

Qualification testing should consist of the pressure testing and vibration testing defined in Section 5.2.1.1.3.

5.2.1.3.2 Acceptance Test Requirements

ASME Code MPVs should be proof-pressure tested at 1.5 × MEOP.

5.2.1.3.3 Special Requirements

ASME Code pressure vessels should be shown to be compatible with the contained fluid(s) and should be verified to be LBB designs.

5.2.2 Composite Pressure Vessels (CPVs)

Pressure vessels fabricated from composite materials (CPVs) must satisfy the requirements for MPVs of Section 5.2.1 with the following exceptions applicable to each design verification analysis approach:

> CPVs with metallic liners are referred to as metal-lined composite-overwrapped pressure vessels (metal-lined COPVs). They may be designed employing either of the two approaches as described in 5.2.1. CPVs without a load-carrying metallic liner may be designed only in accordance with ASME Code.

The LBB or non-LBB failure mode designation for a metal-lined COPV should be based on the characteristics of the liner. Fracture mechanics methodology is not applicable to the composite overwrap.

5.2.2.1 Metal-Lined COPV with Nonhazardous LBB Failure Mode

Applicable fracture mechanics analysis and/or tests should be used to verify the LBB failure mode of the metal liner.

5.2.2.1.1 Factor of Safety Requirements

Requirements of Section 5.2.1.1.1 should be met.

5.2.2.1.2 Safe-Life Analysis Requirements

Requirements of Section 5.2.1.1.2 should be met.

5.2.2.1.3 Qualification Test Requirements

Qualification testing should consist of LBB demonstration of the metal liner and cycle/burst testing of the metal-lined COPV as defined in Section 5.2.1.1.3. In particular, the effect of the liner sizing operation on the fracture mechanics characteristics of the metal liner should be accounted for in the LBB evaluation.

5.2.2.1.4 Acceptance Test Requirements

Acceptance tests should be conducted as defined in Section 5.2.1.1.4. The substitution of the metal liner sizing operation for acceptance test is acceptable provided the requirements of Section 5.2.1.1.4 are satisfied.

5.2.2.1.5 Recertification Test Requirements

Requirements of Section 5.2.1.1.6 should be met.

5.2.2.2 Metal-Lined COPVs with Non-LBB or Hazardous LBB Failure Mode

This section is applicable only to COPVs with metal liners that exhibit non-LBB or hazardous LBB failure modes.

5.2.2.2.1 Factor of Safety Requirements

Unless otherwise specified, the minimum burst factor should be 1.5.

5.2.2.2.2 Safe-Life Demonstration Requirements

Requirements of Section 5.2.1.1.2 should apply to the metal liner. Conventional fatigue life analysis of the composite overwrap must verify that the liner is the critical safe-life component. Analysis should show the safe-life of the overwrap to be a factor of 10 longer than the safe-life of the liner.

5.2.2.2.3 Qualification Test Requirements

Requirements of Section 5.2.1.1.4 should be met.

5.2.2.2.4 Acceptance Test Requirements

Acceptance tests should be conducted as defined in Section 5.2.1.1.5. Substitution of the metal liner sizing operation for acceptance testing is acceptable, provided the requirements of Section 5.2.1.1.5

are satisfied. The metal liner should not leak at the proof test pressure. An additional cryogenic-type proof test of the liner prior to composite overwrap may be required to adequately verify the initial flaw size in the liner.

5.2.2.2.5 Recertification Test Requirements

Requirements of Section 5.2.1.1.5 should be met.

5.2.3 CPVs Designed Employing the ASME Boiler Code

CPVs may be designed and manufactured per the rules of the ASME Boiler and Pressure Vessel Code, Section X.

5.2.3.1 Safety of Factor Requirements

The minimum safety factor for burst is 6.

5.2.3.2 Safe-Life Requirements

Not required.

5.2.3.3 Qualification Test Requirements

Qualification testing should consist of the cycle testing and random vibration testing defined in Section 5.2.1.1.3

5.2.3.4 Acceptance Test Requirements

Acceptance test requirements are as specified in the Code. The proof pressure test should be conducted at 1.5 × MEOP.

6. Recommended Key Requirements and Implementation Guidelines for MPVs

In the design, analysis, test, inspection, operation and maintenance of MPVs used in RLVs, the following are essential elements that must be addressed to assure safety of crew and passengers:

- System Analysis
- Strength
- Fracture Control
- Leak-Before-Burst (LBB) Failure Mode
- Fatigue (Safe-Life)
- Damage Tolerance
- Inspection
- Acceptance Proof Tests
- Qualification Tests
- Operation and Maintenance
- Repair and Refurbishment

Recommended requirements associated with the above-listed elements are presented in the following sections. The majority of the recommended requirements are derived based on AIAA S-080. Guidelines about how to implement these requirements are also presented. Some of the requirements and guidelines provided herein are also applicable to COPVs and will not be repeated in Section 7, which addresses COPVs only.

6.1 System Analysis

6.1.1 System Analysis Requirements

The following system analysis requirements are recommended:

- A thorough analysis of the pressure system in which the MPV will be operated should be performed to establish the correct MEOP (or MDP). The effect of each of the other component operating parameters on the MEOP (or MDP) should be considered; pressure regulator lock-up characteristics, valve actuation and water hammer, and any external loads should be evaluated for the entire service life of the MPV.
- MPVs designed, fabricated, inspected, and tested in accordance with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, Division a and 2, should comply with system analysis requirements.

6.1.2 Guidelines for System Analysis Requirements

6.1.2.1 System Analysis Ingredients

It is the responsibility of the primary contractor (or procuring agency) for the RLV in which the MPV will be used to perform detailed system analysis. In addition to establishing the correct MEOP (or MDP), the system analysis should determine that the operation, interaction, or sequencing of pressure components will not lead to damage to the RLV or associated ground support equipment. The analysis should identify any single malfunction or personnel error in operation of any component that will create conditions leading to an unacceptable risk to ground operating personnel, flight crew and passengers. The analysis should also evaluate any secondary or subsequent occurrence, failure, or component malfunction that, initiated by a primary failure, could result in personnel injury. Such items identified by the analysis should be designated safety critical and will require the following considerations.

1) Specific design action;
2) Special safety operating requirements;
3) Specific hazard identification and proposed corrective action or control; and
4) Special safety supervision.

6.1.2.2 System Analysis Data

Systems analysis data should show that:

1) The system provides the capability of maintaining all PVs in a safe condition in the event of interruption of any process or control sequence at any time during test or countdown.
2) Redundant pressure relief devices, if required, should have mutually independent pressure escape routes.
3) In systems where pressure regulator failure may involve critical hazard to the crew or mission success, regulation should be redundant. Passive redundant systems should include automatic switch-over.
4) When the hazardous effects of safety-critical failures or malfunctions are prevented through the use of redundant components or systems, it should be mandatory that all such redundant components or systems are operational prior to the initiation of irreversible portions of safety-critical operations or events.

6.1.2.3 ASME Code MPVs

When PVs that are designed, fabricated and tested in accordance with (IAW) ASME Code, the system analysis is still needed in order to assure that no surprises will arise. However, Maximum Operating Pressure (MOP) instead of MEOP is usually used as the baseline pressure IAW ASME Code.

6.2 Strength

The static strength of a PV is one of the most important parameters in the design. The recommended general design requirements on strength are stated herein in Section 6.2.1. Guidelines for implementing these requirements are provided in Section 6.2.2.

6.2.1 Strength Requirements

The following strength requirements are recommended:

1) All MPVs should possess sufficient strength to withstand limit loads and simultaneously occurring internal pressures in the expected operating environments throughout their respective service lives without experiencing detrimental deformation. They should also be capable of withstanding ultimate loads and simultaneously occurring internal pressures in the expected operating environment without experiencing rupture or collapse.

2) MPVs should be capable of withstanding ultimate loads and ultimate external pressure (destablilizing) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

3) All MPVs should sustain proof pressure without incurring gross yielding or detrimental deformation. MPVs should be tested to verify design burst pressure without burst in design verification tests. For MPVs used in RLVs with crew and passengers, the minimum ultimate design safety factor for external loads should be 1.4, and the minimum design burst factor should be 1.5. When proof tests are conducted at temperatures other than design temperatures, the change in material properties at the proof temperature should be accounted for in determining proof pressure.

4) The margin of safety (MS) should be positive and determined by analysis or test at design ultimate and, when appropriate, design limit levels at the temperature expected for all critical conditions.

6.2.2 Guidelines for Strength Requirements

For MPVs used in RLVs, the highest external pressure is the atmospheric pressure that they will experience during launch and landing. Therefore, the most critical failure mode of an MPV is rupture. At ultimate load and pressure, an MPV should not rupture. Ultimate load should be the ultimate design safety factor times limit load. The minimum ultimate design safety factor for external load is usually 1.4 for systems with flight crew and passengers and 1.25 for systems without flight crew and passengers. Limit loads are usually developed from dynamic load analysis that includes various flight events such as lift-off, engine ignition, aerodynamic conditions, maneuvering, separation, reentry, and landing. MEOP is commonly used as the baseline pressure. However, for some space systems such as the Space Shuttle and the International Space Station, MDP is required to be used as the baseline internal pressure.

In general, compliance to specification may be verified primarily by analysis and/or testing as follows:

- **Analysis:** This category includes all the analyses such as stress analysis, deflection/deformation analysis, margin of safety analysis, and the related load and thermal analyses. LBB failure mode prediction, fatigue analysis, and damage tolerance (safe-life) analysis are also in this category.
- **Testing:** This category includes all load and/or pressure tests such as proof testing, LBB demonstration testing, damage tolerance (safe-life) testing, and design burst tests. These tests may be performed at component level, unit level, or subsystem level. These tests may be performed in the development phase, qualification phase, and individual flight article acceptance phase.

However, verification can be achieved by inspection alone or combined with other methods. Sometimes, it can be even justified by similarity analysis.

- **Inspection:** This category includes all the physical characteristics that determine compliance of the design requirements. NDE and other general inspections such as dimension check and functional check are in this category.
- **Similarity:** Similarity analysis may be used where it can be shown that the article is similar or identical in design, manufacturing process and quality control to another article that has been previously certified to equivalent or more stringent criteria.

Strength verification of an MPV usually requires structural (stress/strain/displacement) analysis, random vibration test and burst test in the qualification program, and proof test in the acceptance program. For a proto-flight system, a burst test may not be required if a higher-than-usual proof test factor is used in the acceptance test program and if the fatigue analysis shows that the fatigue (safe-life) exceeds 10 times service-life. The random vibration test is sometimes omitted if the boss design is very simple and if other tests can envelop the environment. There are rare situations where the strength of an MPV is verified by similarity plus individual acceptance proof test. However, this approach is not recommended for RLV applications because flight crew and passengers can be affected.

6.2.2.1 Structural Analysis Guidelines

For MPVs, a detailed and comprehensive structural analysis should be performed. The structural analysis usually consists of stress (or strain) analysis and deformation (deflection) analysis. The structural analysis should determine stresses (or strains) and displacement resulting from the combined effects of internal pressure, ground and flight external loads, and temperature gradient as appropriate. The following stress combination scheme is recommended:

$$K_1 S_{\text{external}} + K_2 S_{\text{thermal}} + K_3 S_{\text{pressure}} \leq \text{Ultimate stress}$$

where:

K_1 = design factor of safety when the term is additive to the algebraic sum, $\sum L$

K_1 = 0 applied to minimum external stresses when the term is subtractive to the algebraic sum, $\sum L$

K_2 = design factor of safety when thermal stresses are additive to the algebraic sum, $\sum L$

K_2 = 0 when thermal stresses are subtractive to the algebraic sum, $\sum L$

K_3 = design factor of safety when pressure-induced stresses are additive to the algebraic sum, $\sum L$

K_3 = 1.0 when pressure-induced stresses are subtractive to the algebraic sum, $\sum L$

$S_{\text{mechanical}}$ = stresses due to external loads; e.g., inertial loads, aerodynamic pressure

S_{thermal} = stresses due to thermally induced loads

S_{pressure} = stresses due to internal pressure

Basic data used for the structural analysis include the following information:

- Structural configuration, geometry and gauges. Minimum material gauges identified in the drawing should be used.
- Material's mechanical properties and strength allowables.
- Loading cases list, associated temperatures, and other environments such as stress-corrosion.
- Design burst factor and yield factor.

Either classic closed-form solutions or numerical methods including finite element and finite difference should be used to perform the structural analysis of an MPV. For simple geometry and external loading, closed solutions are very useful for the first-order stress estimation. For example, the following simple solutions can be used to determine the hoop and axial stress of a cylindrical MPV in the membrane section:

$$\text{Hoop stress} = PR/t$$

$$\text{Axial stress} = PR/2t$$

where P is the internal pressure, R is the radius of the cylinder, and t is the wall thickness.

For a spherical MPV, the membrane stress can be determined using the following formula:

$$\text{Hoop stress} = PR/2t$$

Finite element analysis (FEA) is a very versatile tool for modeling the response of an MPV with a complex geometry subjected to complex loading/pressure conditions. Numerous finite element software packages are used in the industry. Examples include COSMOS (Ref. 7), NASTRAN (Ref. 8), and ABAQUES (Ref. 9). These software packages have been verified by the users and can therefore be used without reverification. Newly developed software should be verified by comparing calculation results with known theoretical results, or results obtained by using other verified software, and/or known test data.

6.3 Fracture Control

All MPVs are potentially fracture-critical because bursting of a highly pressurized gaseous metal tank can result in the stored energy being converted to a destructive blast wave that can destroy surrounding structures, and the broken metal pieces can cause severe injuries or fatalities to nearby personnel. A leaking liquid propellant storage tank can also be dangerous because many propellants present toxicity hazards to ground personnel during handling, installation, and operation. Furthermore, a leaking gas tank may jeopardize the planned space mission. These hazards necessitate the need for fracture control requirements for MPVs. Recommended fracture control requirements are specified in Section 6.3.1, and the corresponding implementation guidelines are provided in Section 6.3.2.

6.3.1 Fracture Control Requirements

The following fracture control requirements are recommended for MPVs:

All MPVs in crewed RLVs should be identified as potential fracture-critical parts and placed under fracture control. A fracture control plan (FCP) should be prepared to assure safe operation and achieve mission success. At a minimum, the FCP should describe methods and procedures for the following:

1) Fracture-critical classification (nonhazardous LBB, hazardous LBB, or non-LBB);
2) Fatigue (safe-life) analysis/testing or damage-tolerance analysis/testing to determine acceptability of the hardware;
3) Nondestructive inspection/evaluation (NDI/NDE)
4) Control of materials, manufacturing processes, testing, design changes, transportation and handling, operation, maintenance, repair and refurbishment;
5) Manufacturing process verification and control; and
6) In-service inspection and verification.

An appropriate level of traceability should be maintained throughout development, manufacturing, testing, and all operational phases of the MPV. A log should be maintained to record all load-inducing events and associated environmental conditions occurring during the time period from fabrication to the end of the service life of the vessel. Engineering drawings should contain notes that identify the vessel as fracture-critical and specify the appropriate NDE or other flaw-screening method to be used on the vessel.

At a minimum, changes in design or process specifications, manufacturing discrepancies, repairs, and finished part modifications for all vessels should be reviewed to ascertain that the vessels still meet fracture control requirements.

6.3.2 Guidelines for Fracture Control Requirements

In the fracture control program, the first step is to develop an FCP, which describes how fracture control will be achieved. It should list all of the specific activities required to satisfy fracture control. These include: determining the vessel's failure mode; using fatigue analysis/test to demonstrate fatigue (safe-life) or using damage tolerance analysis/test to demonstrate damage-tolerance life; employing NDE or proof test logic to establish allowable initial flaw sizes and shapes; disposition of detected flaws; etc. The following sections provide guidelines for each of these activities.

6.3.2.1 Failure Modes

For an MPV, the first step in fracture control is to establish failure modes. Three failure modes are classified as follows:

- LBB nonhazardous
- LBB hazardous
- Non-LBB

Requirements for LBB failure mode demonstration and demonstration approaches are described in Section 6.4.

6.3.2.2 Fatigue Demonstration

For MPVs whose failure modes are LBB nonhazardous, fatigue lives can be demonstrated by conventional fatigue analysis or testing. The fatigue analysis should assume that the MPV does not contain cracks. Nominal values of fatigue characteristics including stress-life (S-N) data and strain-life (ε-N) data or the structural materials should be used. These data should be taken from reliable sources such as MIL-HDBK-5J and aerospace structural metals handbooks.

Note: MIL-HDBK-5J, "Metallic Materials and Elements for Aerospace Vehicle Structures," dated January 31, 2003, was cancelled May 5, 2004. Future acquisitions are referred to DOT/FAA/AR-MMPDS-01, "Metallic Materials Properties Development and Standardization (MMPDS)," but users are cautioned to evaluate this latter document for their particular application before using it as a replacement. For PVs, the requirements in MIL-HDBK-5J remain proven and valid. Although it has been cancelled, this document remains available on DOD's Acquisition Streamlining and Standardization Information System (ASSIST) website < http://assist.daps.dla.mil/online/start/ > at no charge.

The analysis should account for the spectra of expected operating loads, pressures, and environments. For MPVs operated in the elastic range, a conventional fatigue damage accumulation technique, Minor's Rule, is a simple method for handling variable amplitude loading. For MPVs operated in the elastic-plastic range, other fatigue analysis methods such as the Manson-Coffin equation can be used. Appendix A describes relevant fatigue analysis methods.

6.3.2.3 Damage Tolerance Demonstration

An MPV whose failure mode is LBB hazardous or non-LBB should be demonstrated by analysis or test that it meets damage tolerance requirements as described in Section 6.5.

6.3.2.4 NDE

State-of-the-art NDE techniques should be used to detect potential flaws that might exist in the MPVs. The probability of detection (POD) of the NDE technique selected should have a required 90% probability with 95% statistical confidence. The industry recognized statistical approaches for a few commonly used NDE techniques are presented in Section 6.5.2.2.1 for detail.

6.3.2.5 Pressure Cycle Log

A log for all pressurization activities including component proof testing, system proof testing, re-proof testing (if applicable), leaking tests, function checks, and fill and refill pressurization cycles should be kept and updated.

6.3.2.6 Fracture Control Report

To certify fracture control compliance of an MPV, a fracture control summary report should be prepared. This report should provide the following information:

- A statement of the failure mode and the associated demonstration analysis/or testing results
- Identification of the NDE method and/or proof test results for initial flaw sizes
- Material certification for fracture toughness and other related crack growth data
- An updated pressure cycle log
- Damage-tolerance life analysis/or testing results
- Any material review board (MRB) action
- The repaired information
- Updated damage-tolerance life analysis and/or testing results

6.4 Failure Mode

To improve safety, MPVs used in RLVs with flight crew and passengers should be designed to have a leak-before-burst (LBB) failure mode. This design practice is also recommended for RLVs without people on board. For an LBB failure mode, a flaw or cracklike defect on the wall surface or embedded inside the wall on an MPV will grow through the wall to become a through-crack, thus creating an opening in the wall. If the opening is sufficiently large, the fluid (especially compressed gas) contained in the vessel will leak out rapidly, thereby causing rapid reduction of internal pressure. Consequently, the pressure-induced stress will decrease to a level that will result in the corresponding stress-intensity factor being much smaller than the fracture toughness ($K < K_C$), and the crack will remain stable and not cause catastrophic failure. To accomplish this goal, many approaches can be taken in the design of an MPV. Use of a tough material is the most effective approach. Another approach is to increase the vessel thickness sufficiently to assure that pressure-induced stresses—and hence the corresponding stress intensity factor—will be reduced.

An MPV that exhibits LBB failure is classified into two categories, depending on the consequences of leakage:

- LBB nonhazardous
- LBB hazardous

MPVs that store nonhazardous fluids such as helium and nitrogen gases bottles with LBB failure modes are classified as LBB nonhazardous. Leakage of those MPVs will not create hazardous environments to the crew or the passengers of an RLV.

MPVs used to store hazardous fluids such as hydrazine (HZ), and liquid oxygen (LOX) propellant tanks, are classified as LBB hazardous. A leaking propellant tank will create a hazardous environment, putting the crew and the passengers in danger.

6.4.1 LBB Failure Mode Demonstration Requirements

The following LBB failure mode demonstration requirements are recommended:

- When an LBB failure mode demonstration is required, fracture mechanics principles should be employed. It should be shown by analysis or test that at MEOP (or MDP), both of the following conditions are satisfied: (1) an initial surface flaw with a flaw shape (a/2c) ranging from 0.1 to 0.5 will not fail, i.e., $K < K_{IE}$ and (2) this surface flaw will grow through the wall of the pressurized hardware to become a through-crack with a minimum length of ten (10) times the wall thickness and remain stable.
- If the LBB failure mode needs to be demonstrated by test, the testing may be conducted on coupons that duplicate the materials (parent materials, weld-joints, and heat-affected zone) and thickness of the pressure vessel or on a pressure vessel representative of the flight hardware. Test specimens should contain a prefabricated part-through crack. Fatigue load cycles should be applied to the test specimen with maximum stress corresponding to the MEOP (or MDP) level and minimum stress kept to zero, until the part-through crack propagates through the specimen's thickness to become a through-crack. LBB failure mode is determined if the length of the through-crack becomes greater than or equal to 10 times the specimen thickness and remains stable. The LBB testing should be conducted to establish that all critical areas will exhibit an LBB mode of failure.

6.4.2 Guidelines for LBB Failure Mode Demonstration Requirements

The strength requirements specified in Section 6.2.1 state that all MPVs should sustain proof pressure without incurring gross yielding or detrimental deformation. Since the minimum proof test level should be 1.25 × MEOP, therefore, at MEOP, all the critical areas of an MPV should not be stressed into the plastic region of the material. The LBB failure mode can then be demonstrated by analysis employing the principles of linear elastic fracture mechanics (LEFM), i.e., the fracture behavior can be characterized by the stress intensity factor, K, a parameter derived from LEFM. A brief discussion of LEFM methodology is presented in Appendix B.

To meet the first condition stated in Section 6.4.1, the analysis should show that a surface flaw with a crack shape (a/2c) ranging from 0.1 to 0.5 would not fail as a part-through crack. This implies that all critical regions of an MPV should be shown to have the stress intensity factor of a part-through crack (surface flaw), K_{ptc}, which has a depth "a" that just reaches the thickness t (i.e., a = t), having a value smaller than or equal to the surface flaw fracture toughness, K_{Ie}. In simple mathematical terms, this can be expressed as

$$K_{ptc}\,(a{=}t) \;<\; K_{Ie}$$

To meet the second condition in Section 6.4.1, the analysis should show the stress intensity factor of a through-crack

$$K_{(2c=10t)} \leq K_c$$

where K = stress intensity of a through-crack in the opening mode, Mode I,
$2c$ = total length of the assumed through-crack,
t = thickness of the hardware, and
K_c = material's fracture toughness, most likely mixed-mode fracture toughness

The "10t" requirement was introduced in NASA fracture control requirements for Space Station (NASA-SSP-30558, Rev. B, 1994). This length requirement is consistent with the first condition: a surface flaw with a crack shape (a/2c) = 0.1 will not fail as a part-through crack before it grows through the wall thickness, i.e., a = t. At this condition, the length is 2c = 10t.

For a typical spaceflight MPV, its thickness is around 0.05 in. Thus a through-thickness crack with a total length, 2c = 0.5 in., is considered large enough to cause the fast release of stored fluids, especially helium gases.

For MPVs, the LBB demonstration can be also done by test. This is usually done when a new material (or heat treat condition) is used where there is no reliable fracture toughness database. The test specimens used in the LBB demonstration testing can be either coupons or a full-scale article. When coupons are used, their material and fracture properties should be that representative to the parent metals, weld-region, and heat-affected zone (HAZ). The thickness of the test coupons should be also identical to the thickness of the critical stress regions. The induced surface flaws with various a/2c ratios, ranging from 0.5 to 0.1, should be fabricated using an electric discharge machining (EDM) or equivalent notching process. Precracking procedures should be applied to assure that fatigue crack has been initiated from the induced notch. Fatigue stress cycles from zero stress to the maximum stress corresponding to MEOP based on stress analysis should be applied to the specimen until the surface flaw grows through the thickness of the specimen and becomes a through-thickness crack, thereby meeting the first requirements specified in 6.4.1. Test specimens should be continuously cycled at the same minimum and maximum stresses until $2c \geq 10t$. At this crack size, the specimen should be loaded at maximum stress for a minimum of 5 minutes. If the crack remains stable after a 5-minute hold time, LBB is successfully demonstrated. The LBB test is a fracture test, not a crack-life test; therefore, the number of cycles that are applied to the specimens is not a part of the success criteria.

If the full-scale vessel is to be used for testing, the initial flaws are better fabricated on the outer surface of the vessel for easy monitoring of the crack growth. The test cycle stresses will be induced by internal pressure. Charge and discharge of each cycle should be maintained at a appropriate rate. After the surface flaw penetrates the thickness of the MPV, leakage may have developed and the internal pressure of the vessel may drop very fast. Before the crack length propagates to ten times the wall thickness, internal pressure should be maintained by pumping the vessel with more test fluid. When the pump rate increases to its maximum allowable rate and still cannot overcome the leakage, the test should be discontinued. Under this condition, the LBB failure mode is considered to have been demonstrated.

6.4.3 Non-LBB Failure Mode

MPVs that cannot be shown to meet the LBB failure mode requirements are referred to as MPVs with non-LBB failure mode. Fracture control requirements described in Section 6.3.1 should be imposed on those MPVs.

6.4.4 Hazardous LBB Failure Mode

For MPVs that exhibit LBB failure mode but contain hazardous fluids such as hydrazine propellant, the fracture control requirements recommended in Section 6.3.1 should also be met.

6.5 Damage Tolerance

MPVs whose failure modes are non-LBB should be identified as fracture-critical items and be placed under fracture control. MPVs that exhibit LBB failure mode but contain hazardous fluids should also be identified as fracture-critical items and placed under fracture control. A key fracture control requirement for fracture-critical items is demonstration that they are damage tolerant.

6.5.1 Damage Tolerance Demonstration Requirements

For damage tolerance demonstration, the requirements discussed below are recommended. Fracture-critical MPVs should be demonstrated to possess damage tolerance capability. The demonstration can be achieved by performing a damage tolerance analysis or by damage tolerance testing.

6.5.1.1 Damage Tolerance Analysis

Damage tolerance analysis should be based on LEFM principles. Undetected flaws should be assumed to be in critical locations and in the most unfavorable orientation with respect to the applied stress and material properties. Flaws sizes should be either determined using appropriate NDE technique(s) or defined by acceptance proof testing. A flaw shape (a/2c) in the range of 0.1 to 0.5 should be assumed.

Nominal values of fracture toughness and fatigue crack growth rate data associated with each alloy, temper, product form, thermal environment, and chemical environment should be used in the damage tolerance analysis. However, if proof test logic is used for determining initial flaw size, an upper-bound fracture toughness value should be used in determining both the initial flaw size and the critical flaw size at fracture.

MPVs that experience sustained stresses should also show that the corresponding maximum stress intensity factor (K_{max}) during sustained load in operation is less than the environment-aided fracture toughness data in the appropriate environment, i.e., K_{EAIC}. Detrimental tensile residual stresses should be included in the analysis.

Proven hand-calculation methods or a state-of-the-art crack growth software package should be used to conduct the damage tolerance analysis. Flaw shape (a/2c or a/c) changes should be accounted for in the analysis. Retardation of crack growth rates from variable amplitude loading should not be considered unless otherwise specified. A life factor of four should be used in the damage tolerance analysis. For MPVs accessible for periodic inspection and repair, it should be shown that the flaw will not grow to critical dimensions for at least four (4) times the between-scheduled inspection intervals and/or refurbishment.

A damage tolerance analysis report should be prepared to delineate the following:

a. Fracture mechanics data (fracture toughness and fatigue crack growth rates);

b. Loading spectrum and environments;

c. NDE method(s) and corresponding initial sizes;

d. Analysis assumptions and rationale;

e. Calculation methodology;

f. Summary of significant results; and

g. References.

This report should be closely coordinated with the stress analysis report and periodically revised during the program life.

6.5.1.2 Damage Tolerance Testing

Damage tolerance testing in lieu of damage tolerance analysis is an acceptable alternative to demonstrate the damage tolerance ability of an MPV, provided that, in addition to following a quality assurance program for each MPV, a crack growth test program is implemented on pre-flawed specimens representative of the structure design. The test specimens can be either uniaxial coupons or full-scale MPVs. The prefabricated flaws should not be less than the flaw sizes established by the NDE method(s) selected for acceptance proof test. The shape (a/2c) of surface flaws should range from 0.1 to 0.5. Flaw shape (a/c) for corner cracks should range from 0.2 to 1.0. Damage tolerance requirements are considered to have been demonstrated when the pre-flawed test specimens successfully sustain the limit loads and pressure cycles in the expected operating environments without leaking. A life factor of four (4) on specified service life should be applied in the damage tolerance testing.

A damage tolerance test report should be prepared and should include the following:

a. Test specimen description;

b. Test setup description;

c. Test loading spectrum and environment;

d. Test procedures;

e. Test results; and

f. References.

6.5.2 Guidelines for Damage Tolerance Demonstration

In the earlier years of military aircraft industry, the term “damage tolerance” was applied to discrete damage such as battle damage. Since the 1970s, the military aircraft industry has included, as a part of damage tolerance, undetected cracks in metallic airframe structures. The Aircraft Structural Integrity Program (ASIP), defined in MIL-STD-1530B (first issued in 1974), Joint Service Specification Guide (JSSG) 2006, “Structures,” and FAA regulations such as 14 CFR parts 23 and 25, use the term “damage tolerance” in application to both metallic and composite structures.

Demonstration of damage tolerance can be accomplished by analysis or testing.

6.5.2.1 Damage Tolerance Analysis Methodology

Damage tolerance analysis has been referred to as “safe-life analysis” in the space industry since the start of the NASA Space Shuttle Program. However, in the recent fracture control standard issued by NASA, this term has been changed to damage tolerance analysis to be consistent with aircraft industry and to avoid confusion with the definition of safe-life used in the commercial aircraft industry (indicated as “total fatigue life”).

The following are essential ingredients for performing an LEFM-based crack growth analysis:

1) Initial crack size (a_i) and shape (a/2c)
2) Fatigue stress/environment spectrum
3) Fracture toughness (K_c) data
4) Fatigue crack growth rate (da/dN) data

6.5.2.1.1 Initial Crack Size and Shape Assumption

The initial crack type, shape and sizes assumed in the crack-growth analysis are usually based on the NDE technique that will be used for inspection of the MPVs. In some instances, however, a so-called "proof test logic" based on LEFM is used.

6.5.2.1.2 Using NDE

In most cases, initial crack sizes assumed in the crack growth analysis are based on the specific NDE technique(s) that are used on flight hardware. In the fracture control requirements standard for Space Shuttle payloads, the initial flaw sizes assumed in the fracture mechanics safe-life analysis are given in Table 6-1 (Ref. 10) for the geometries shown in Figure 6-1 (Ref. 10). These are usually identified as the "standard NDE detectable crack sizes." In general, the NDE method is selected for a specific location, and the corresponding crack sizes are used in the safe-life analyses or tests. Dye penetrant is a commonly used NDE technique for MPVs to detect surface flaws or crack-like defects in non-welded regions. In weld regions, radiography (X ray) is often used to detect internal weld-induced defects such as voids, mismatches, and linear indications. Ultrasound can be also used for detecting internal flaws.

When the crack growth analysis shows that the use of a standard initial size for a specific NDE method cannot meet the safe-life requirement, a "Special NDE" technique should be used. The probability of detection (PoD) of a special NDE technique should be demonstrated with 90% reliability and 95% confidence.

For an MPV having very thin (less than 0.025 in.) wall thickness, a Lamb wave ultrasound technique has been demonstrated to be effective. Data have shown that this technique can detect a surface crack with a depth smaller than 0.01 in.

6.5.2.1.3 Using Proof Test Logic Approach

The use of proof pressure test to determine the initial flaw size of an MPV in the safe-life analysis was proposed by Tiffany and Master in the mid-1960s (Ref. 11). As shown in Figure 6-2, if an MPV has successfully passed the proof test, the maximum possible initial flaw size, "a_i", for a flaw that might still exist in the vessel can be determined by the following relationship:

$$a_i \leq a_{cr} = (Q/\pi)\,(K_c / \beta\,\sigma_p)^2$$

where a_{cr} is the critical flaw size at the proof pressure level, Q is the shape factor of an elliptical crack, K_c is the fracture toughness of the vessel's parent material or weld-joint, β is the geometrical correction factor, and σ_p is the stress corresponding to the proof pressure.

Table 6-1. Assumed Initial Crack Size vs. NDI Methods (Source: NASA-STD-5003, Ref. 10)
(U.S. Customary Units, in.)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a	Crack Dimension, c
<u>Eddy Current NDE</u>				
Open Surface	$t \leq 0.05$ $t > 0.05$	Through PTC[1]	t 0.02 0.05	0.05 0.1 0.05
Edge or Hole	$t \leq 0.075$ $t > 0.075$	Through Corner	t 0.05	0.1 0.05
<u>Penetrant NDE</u>				
Open Surface	$t \leq 0.05$ $0.05 < t \leq 0.075$ $t > 0.075$	Through Through PTC	t t 0.025 0.075	0.1 0.15 – t 0.125 0.075
Edge or Hole	$t \leq 0.1$ $t > 0.1$	Through Corner	t 0.1	0.1 0.1
<u>Magnetic Particle NDE</u>				
Open Surface	$t \leq 0.075$ $1 > 0.075$	Through PTC	t 0.038 0.075	0.125 0.188 0.125
Edge or Hole	$t \leq 0.075$ $t > 0.075$	Through Corner	t 0.075	0.25 0.25
<u>Radiographic NDE[2]</u>				
Open Surface	$0.025 \leq t \leq 0.107$ $t > 0.107$	PTC	0.7t 0.7t	0.075 0.7t
<u>Ultrasonic NDE[3]</u>				
Comparable to a Class A quality level				
Open Surface	$t \geq 0.1$	PTC	0.03 0.065	0.15 0.065

<u>Notes</u>:
1. Part-through crack
2. Sizes not applicable to very tight flaws such as forging flaws, or lack of full penetration in butt weld
3. Comparable to Class A quality level of MIL-STD-410

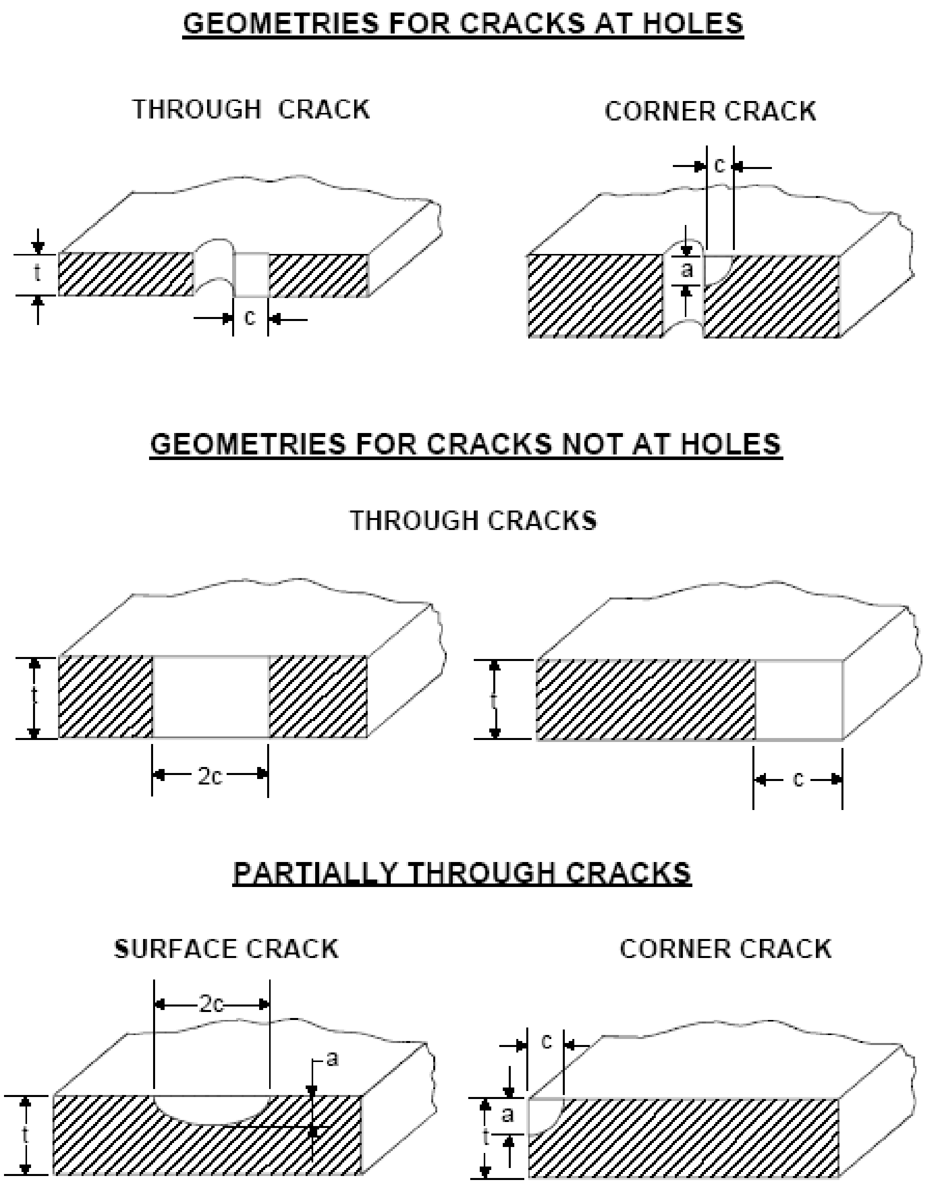


Figure 6-1. Typical crack geometry (source: NASA-STD-5003, Ref. 10).

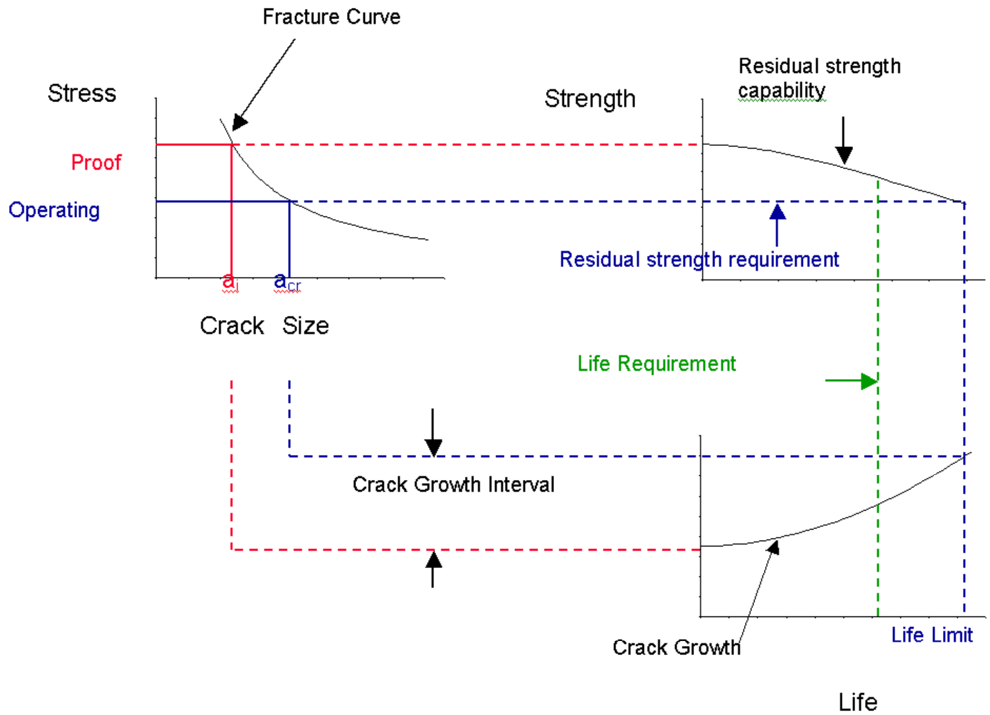


Figure 6-2. Calculation of maximum possible initial flaw size, ai, for flaw in MPV that has successfully passed proof test.

Based on the proof test logic, a_i is considered as the maximum initial flaw size to be used in the safe-life analysis for determining the maximum length to which this crack will grow.

6.5.2.2 Damage-Tolerance Testing

When damage-tolerance life demonstration by test is required, coupons or a flight representative MPV may be used as the test specimens.

6.5.2.2.1 Damage-Tolerance Testing Using Coupons

When coupons are used as test specimens for damage tolerance life demonstration of MPVs, uniaxial coupons that duplicate the vessel material (i.e., wrought material, weld joints or heat-affected zones), processes, and thickness should be used. If the coupons are cut from a full-scale vessel, they should be heated to within 20° of the aging temperature, flattened, and machined flat to produce uniform thickness specimens. The coupons should contain a surface crack and should meet the requirements for validity of an appropriate method from a published standard of a recognized standards institute such as ASTM E-399 (Ref. 12) for center-through cracks and E-740 (Ref. 13) for surface cracks. The size of the surface cracks should not be smaller than the flaw sizes established by the appropriate acceptance NDE methods or by proof test logic. The flaw shape parameter, a/2c, should range from 0.1 to 0.5.

The stress spectrum applied to the coupons should be that established for all pressure cycles to which the vessel will be subjected. The pressure cycles should include proof pressures if NDE is performed before the proof tests. The coupon should be cycled though this spectrum in sequence four (4) times the specified service life. At a minimum, two data points should be tested for each material and form.

After completion of cyclic testing, the crack faces should be separated in a manner to permit measurement of the initial crack sizes to verify conformance to accepted NDE limit sizes.

6.5.2.2.2 Damage-Tolerance Testing Using MPVs

An MPV representative of the flight article (liner materials and processing, liner thickness, configuration, and reinforcing composite stiffness) may be used to demonstrate the required damage tolerance life. Surface cracks should be placed at critical locations. An inert fluid should be used to pressurize the vessel. At least two different flaw-shaped cracks should be tested. After the completion of pressure cycle testing, the vessel should be leak checked to verify that neither leakage nor fracture has occurred during the test.

6.5.2.2.3 Sustained Load Crack Growth Testing

If data do not exist, the sustained load crack growth test of the vessel material can be performed using uniaxial tensile coupons. The stress applied to the coupon during sustained load testing should be the highest stress at the appropriate pressure for that fluid and the sustained load duration. The crack under stress should be exposed to the fluid for a minimum of 1000 hours.

6.6 Disposition of Detected Cracks

When an MPV design has been demonstrated to be damage tolerant, i.e., possess adequate safe-life, that does not imply that a detected crack in a flight vessel is automatically acceptable. It is sometimes erroneously assumed that flight hardware with a crack may be used if the crack does not exceed the “minimum flaw size,” which is sometimes the same as the size of assumed flaws from NDE tests in Table 6-1. Some standards specify general requirements for detected cracks in fracture-critical hardware, as described in Section 6.6.1 below.

6.6.1 Detected Crack Disposition Requirements

The following requirements are recommended:

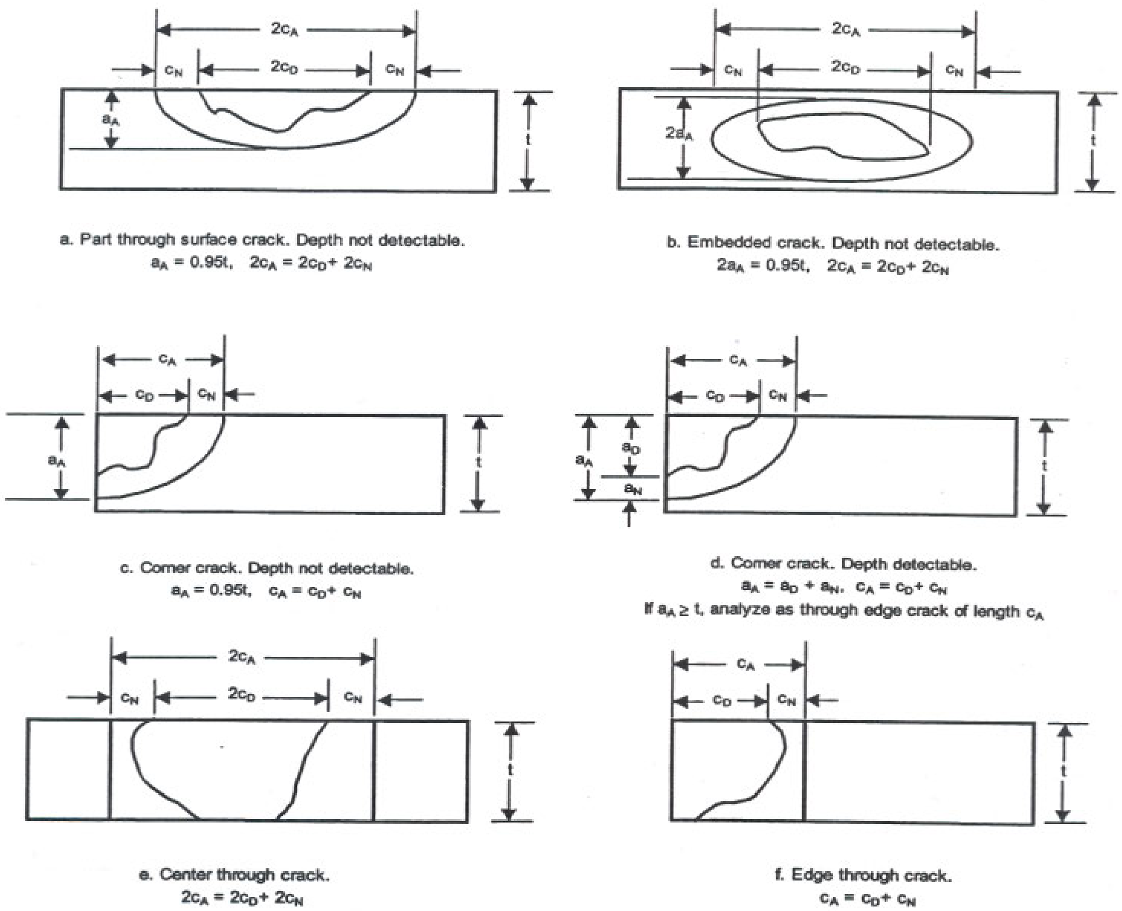
A specific, detailed fracture mechanics analysis (or test) should be performed to justify the use of any fracture-critical flight part with detected crack-like flaws. Approval of the procuring authority must be obtained prior to use of any fracture-critical part containing detected cracks or crack-like defects. Occurrences of detected crack-like flaws should be included in the fracture control summary report along with the basis for acceptability.

A specific damage tolerance assessment should be performed to justify the use of any fracture-critical part with detected cracks. The use of any fracture-critical part must have prior approval of the responsible safety authority. The analysis and rationale for acceptance of detected cracks should be included in the fracture control summary report. The assessment should be made using conservative assumptions regarding the actual maximum crack size, material properties, and all internal and external loads. Additional requirements, including larger factors on crack size, life, and/or fracture than normally used for damage tolerance assessment, may be imposed by the safety authority.

6.6.2 Guidelines for Detected Crack Disposition Requirements

6.6.2.1 Crack Sizes

The crack size used for safe-life analysis must conservatively bound the actual physical size of detected cracks. Since no real crack is semi-elliptical in shape, as assumed in Table 6-1, certain adjustments should be made. NASA Handbook 5010 (Ref. 14) provides a set of guidelines as how to adjust crack sizes in damage tolerance analysis/testing. Figure 6-3 depicts these adjustments schematically for detected cracks or crack-like defects of various sizes with detected and nondetected depths.



Definitions

a	Crack depth or half the crack depth
c	Crack length or half the crack length
t	Part thickness

Subscripts

A	Indicates crack dimension used for analysis
D	Indicates detected crack dimension
N	Indicates the capability of the NDE method used to detect the crack

Figure 6-3. Adjustment of detected crack sizes, for use in damage tolerance analysis/testing.

6.6.2.2 Fracture Properties

Fracture toughness, K_{cr}, used in the safe-life analysis must be a lower bound value, based on available data. If fewer than seven values of materials' K_{cr} are available, the lower bound must be taken as the lower value of the following two cases:

1. The lowest value of all available, applicable data, or
2. The average of the available, applicable data divided by 1.2.

The fatigue crack growth rate, da/dN, used in the safe-life analysis should be upper bound.

6.7 Vibration Test

6.7.1 Vibration Testing Requirements

The following vibration test requirements are recommended:

A maximum expected flight-level vibration environment should be established from the predominant vibration source encountered during the mission. Qualification testing should be performed per MIL-STD-1540 unless it can be shown that the vibration requirement is enveloped by other qualification testing conducted.

6.7.2 Guidelines for Vibration Testing

Techniques are available that can be used to meet the above test requirements. However, the following requirements apply regardless of which technique is selected:

1. Environmental load fixture designs should be provided to the procurement agency for review and approval.
2. Control logic and response limitation techniques should be pre-declared and approved by the procurement agency.

The test article should be the pressure vessel that is used in the qualification test program. It should be mounted to a fixture through the normal mounting points. The vessel should be tested in a minimum of two axes, the mutually independent longitudinal and lateral axes. The mounting fixture(s) should be designed to provide proper stiffness or reaction loads at the mount points. For vibration tests, significant resonant frequencies of the bare mounting fixture and mounted vessel in the fixture should be noted and recorded.

6.7.2.1 Random Vibration Test

The test should be run at 6 dB above flight levels for the flight duration or at 3 dB above flight levels for a duration four (4) times that experienced in flight. The tolerances should be:

(a) ±1.5 dB from zero to 500 Hz and

(b) ±3 dB from 500 to 2000 Hz.

Additional local excursions from these tolerances over a maximum bandwidth of 100 Hz are allowable as specified below:

(a) +3 dB over 100 Hz bandwidth from 500 to 2000 Hz

(b) The overall RMS level should be ±10% about the nominal specified value.

Programmed notches to limit the response of the pressure vessel about the first mode responses in the mutually independent axes are permitted if approved by the procurement agency.

6.7.2.2 Sine Vibration Test

Sinusoidal vibration may be applied as a dwell at discrete frequencies or as a frequency sweep with the frequency varying at a logarithmic rate. The maximum permissible sweep rate is two octaves per minute.

The test should be conducted at an amplitude 25% above flight levels for flight duration. The tolerance about the nominal input level is ±10%. Programmed notches to limit the response of the pressure vessel about the first mode responses in the mutually independent axes are permitted if approved by the procurement agency.

6.7.2.3 Acoustic Test

The pressure vessel should be fully loaded and tested at the greatest acoustic value anticipated. The mounting fixture should emulate the stiffness of the flight system seen by the pressure vessel.

6.7.2.4 Equivalent Static Load Test

Static load testing, in combination with qualification pressure cycle test data, may be used in lieu of vibration testing if it can be demonstrated that the static load test, applied with the appropriate resident pressure, envelops the qualification-level external loads. The demonstration of static structural margins and life margins associated with the number of load application cycles, which would occur under the qualification dynamic excitation environment at the mounting point(s), is required. The analytical assumptions relating to the modal responses and transmissibility of the structure used in defining the equivalent static load should be fully documented and supported by prior testing on similar hardware.

6.7.2.5 Shock Test

Shock testing is required only if the equivalent external load for critical areas of the pressure vessel is not enveloped by the vibration or static load tests.

6.8 Pressure Testing

6.8.1 Recommended Pressure Cycle Test Requirements

The following pressure cycle and burst test requirements are recommended for all MPVs:

All MPVs should be subjected to the pressure cycle to verify their fatigue life capability. The test fixture should emulate the structural response or reaction loads of the flight mounting so that the tested hardware mounting induces axial or radial restrictions on the pressure-driven expansion of the hardware. The requirement for application of external loads in combination with internal pressures during testing should be evaluated based on the relative magnitude and/or destabilizing effect of stresses due to the external load. If limit combined tensile stresses are enveloped by test pressure stresses, the application of external loads should not be required. If the application of external loads is required, the load should be cycled to limit for four (4) times the predicted number of operating cycles of the most severe design condition (e.g., destabilizing load with a constant minimum internal pressure or maximum additive load with a constant maximum expected operating pressure).

The temperature should be consistent with the critical use temperature, or test pressures should be suitably adjusted to account for worst-case temperature effects on static strength and/or fracture toughness.

After pressure cycle testing, the test article should be pressurized to its design burst pressure and held sufficient time for recording. After recording, the pressurization event should be continued until the test article fails catastrophically. The pressure at the catastrophic failure is identified as the real burst pressure of the test vessel. The reason to bring the vessel to actual failure is to verify the margin-of-safety calculations.

6.8.2 Pressure Test Requirements Implementation Guidelines

To conduct a successful pressure test, a test plan should be prepared that clearly delineates the test equipment, test procedure, and test tolerance. Safety concerns should be addressed in the test plan.

6.8.2.1 General Guidelines

Test Setup

In general, pressure testing should be conducted in a test facility with test fixtures strong enough to support the test load/pressure/temperature. The test cell should be well protected to prevent excessive blast wave and fragments as the result of vessel burst, either intentionally or accidentally. A pressure system and leakage check device together with the necessary control system should be provided.

Test Environments

Pressure tests should be performed at predetermined temperature and humidity. In general, acceptance proof pressure tests are conducted at ambient temperature and in laboratory air environment. Qualification pressure tests are usually conducted at the extreme temperature and humidity to which the pressurized hardware item will be subjected in service.

Test Fluid

In general, the test fluid used in a pressure test is liquid such as de-ionized water. Water is used instead of gas to avoid the blast wave caused by suddenly released gas.

Test Level

Pressure tests should be performed at the predetermined pressure and load level. MEOP is usually used as the baseline for pressure, and limit load is usually used as the baseline for external loads. For manned systems such as the Space Shuttle and the International Space Station, maximum design pressure (MDP) should be used as the baseline pressure.

Test Duration

The test duration should be set depending on the type of pressure test. For acceptance proof pressure testing, the duration should be 5 minutes unless there is a technical justification for a shorter duration. The reason for 5 minutes is to let the metallic material have sufficient time to react at a stress level near the material's elastic limit.

NDI

NDI should be performed before the pressure cycle test to establish the initial condition of the test article. Technique(s) used for NDI of MPVs under fracture control should be consistent with the crack detection capability assumed in the damage tolerance safe-life analysis or testing.

Test Tolerances

Unless otherwise provided, the following test tolerances for each test parameter are recommended:

Temperature	±5˚F
Static Load	+5/–0 percent
Pressure	+5/–0 percent

Test Time Duration	+10/–0 percent
Pressure Ramp Rate	±20 percent

6.8.2.2 Pressure Cycle Testing Guidelines

Test Equipment

To assure the safety of the test crew, the test article should be placed in a test chamber having structural members with a demonstrated safety factor of four (4) for ultimate burst strength of the test article. For pressure cycle tests, a pump with plumbing capability twice MEOP or MDP should be used. The pressure should be monitored using a pressure gauge with ±25 psig resolution or better and calibrated to ±1.0% accuracy. It is important to have a backup pressure gauge of the same range and resolution for redundancy. A temperature gauge (thermal meter) should be installed inside the test chamber.

Test Procedure

a. Fill the test article with hydraulic fluid such as de-ionized water. Pneumatic fluid should be used only when required. Check the pressure gauge and temperature gauge to assure that the test pressure and temperature match the required test pressure and temperature within the acceptable tolerances.

b. Pressurize the test article to the required peak pressure and hold the pressure until the pressure gauges are stabilized. Then release the pressure. The pressure ramp rate should be 50 psi/sec.

c. Repeat the above step until the number of cycles that are required in the test plan are completed.

d. Conduct a leak check.

e. Perform post-proof inspection.

Safety Precautions

The test fluid used for pressure cycle tests should be nonhazardous so that unexpected pressure leakage will not create a hazardous environment for the test crew. The test should be conducted in a well protected test pit to contain the blast wave or debris due to the unpredicted catastrophic failure.

6.8.2.3 Burst Testing

Test Setup

In general, pressure testing should be conducted in a test facility with test fixtures strong enough to support the test load/pressure/temperature. The test cell should be well protected to prevent excessive blast wave and fragments as the result of vessel burst, either intentionally or accidentally. A pressure system and leakage check device together with the necessary control system should be provided.

Test Environment

Pressure tests should be performed at predetermined temperature and humidity. In general, acceptance proof pressure tests are conducted at ambient temperature and in laboratory air environment. Qualification pressure tests are usually conducted at the extreme temperature and humidity to which the pressurized hardware item will be subjected in service.

Test Fluid

In general, the test fluid used in a pressure test is hydraulic liquid such as de-ionized water. Water is used instead of gas is to avoid the blast wave caused by suddenly released gas.

Test Duration

After the test pressure has reached the vessel's design burst pressure, the pressure should be held 30 more seconds to further increase the pressure until the vessel bursts or to stop the test.

6.9 Safe Operations

6.9.1 Safe-Operation Requirements

The following safe-operation requirements are recommended:

Safe operating limits should be established for all MPVs, based on the appropriate analysis and testing employed in its design and qualification test program. These safe-operating limits should be summarized in a format that will provide rapid visibility of the important structural characteristics and capability. The desired information should include, but not be limited to, such data as fabrication materials, critical design conditions, MEOP, nominal operating or working pressure, proof pressure, number of pressure cycles, design burst pressure, pressurization and depressurization, operational system fluid, cleaning agent, NDI techniques employed, permissible thermal and chemical environments, minimum margin of safety, and potential failure mode. For MPVs with a potential brittle fracture failure mode, the critical flaw sizes and maximum permissible flaw sizes should also be included. Appropriate references to design drawings, detail analyses, inspection records, test reports, and other backup documentation should be indicated.

6.9.2 Guidelines for Safe Operation

It is good practice to prepare a detailed fracture control summary that documents the damage tolerance life analysis and/or test results, together with other relevant detailed information, to facilitate review by safety personnel so that they can make a timely decision regarding use of the MPV. At a minimum, the following data should be included in the summary:

- MPV Name and Usage
- Drawing Number
- Material and Process Control Summary
- Corrosion Control Summary
- Potential Failure Mode Prediction Results
- Fatigue (Safe-Life) Analysis / Test Report (if failure mode is nonhazardous LBB)
- Inspection Schedule and NDE Techniques
- Crack Growth Analysis / Test Report
- MEOP
- Proof Pressure and Environment
- Leak Check Pressure and Other Pressure Cycle History

- Allowable Pressure Cycles
- Applied Pressure Cycles to Date (Prior to Review)
- Storage Environment, Time, and General Inspection
- Refurbishment Records and Recertification Document (when applicable)
- Waiver Documents (when applicable)

6.10 Inspection and Maintenance

6.10.1 Inspection and Maintenance Requirements

The following inspection and maintenance requirements are recommended:

The results of appropriate stress and damage tolerance (safe-life) analyses should be used in conjunction with the appropriate results from the structural development and qualification tests to develop a quantitative approach to inspection.

Allowable defect size limits should be established for each MPV so that the required inspection interval and repair schedule can be established to maintain the vessel to the requirements of this and other applicable documents. NDI technique(s), and inspection procedures to reliably detect defects and determine flaw size under the condition of use, should be developed for use in the field and at depot levels. Procedures should be established for recording, tracking, and analyzing operational data as it is accumulated to identify critical areas requiring corrective actions. Analyses should include prediction of remaining life and reassessment of required inspection intervals.

6.10.2 Guidelines for Inspection and Maintenance Requirements

It is important for each MPV used in an RLV that the inspection techniques used in the field or at the depot level be the same as those used in the manufacturing facility, to help ensure that when re-inspection is performed, there are no discrepancies on the PoD. If this is not feasible, then the allowable defect size limit should be reestablished based on the PoD of the NDI used in the field or at the depot level.

During re-inspection, it is not recommended that an MPV be disassembled from the pressure subsystem because disassembly and reassembly creates chances to damage other pressure components. Examples of such damage could be breaking the factory seals at the line-fitting joints or inducing excessive bending to the fluid lines.

6.11 Repair and Refurbishment

6.11.1 Repair and Refurbishment Requirements

The following repair and refurbishment requirements are recommended:

When inspections reveal structural damage or defects exceeding the permissible levels, the damaged MPV should be repaired, refurbished, or replaced, as appropriate. All repaired or refurbished MPVs should be recertified after each repair and refurbishment using the applicable acceptance test procedure for new hardware to verify their structural integrity and to establish their suitability for continued service. All repair activity should be a Material Review Board (MRB) activity, which requires approval of the procurement agency.

6.11.2 Guidelines for Repair and Refurbishment Requirements

The level of recertification of an MPV after each repair should be decided by the MRB. Unless it is agreed by the safety authority and procurement agency, the repaired MPV should be subjected to another proof pressure test. NDE should be conducted at the repaired area and at unrepaired weld joints after proof testing. Also, a leak check should be conducted after the re-proof test.

6.12 Special Topics

6.12.1 Post-Proof-Test NDE

The technical necessity and value of post-proof-NDE on welds has been a hot topic of discussion. Questions usually center around “why,” “how,” and “what are the consequences if it is not done?” Some relevant explanations and guidelines are provided below.

For an MPV that contains hazardous fluids or exhibits a non-LBB failure mode, fracture control is required that includes damage tolerance (safe-life) analysis or test and NDE. Post-proof NDE provides information about the condition of those vessels after proof test but before they are subjected to other tests and put into service. This is a straightforward safety measurement. However, for mission success, establishing the initial condition before the PV is put into use is also important. In general, post-proof NDE provides many benefits for detecting as-manufactured flaws in MPVs that are otherwise difficult to predict. The proof test enhances the NDE capability to discover problems due to:

(a) Latent defects

(b) Weld repairs, overlaps, intersections, and porosity

(c) Weld geometry, including peaking and mismatch

(d) Assembly stress

(e) Workmanship

7. Recommended Key Requirements and Implementation Guidelines for COPVs

With the following additions, the requirements in Section 6 on MPVs are also applicable to COPVs:

- Composite Material Strength Design Allowables
- Stress Rupture Life
- Impact Damage Control

7.1 Composite Material Strength Design Allowables

7.1.1 Requirements for Composite Material Strength Allowables

The following composite material strength allowable requirements are recommended:

A-basis strength allowables should be determined from burst testing of subscale and/or full-scale composite vessels. If the A-basis fiber strength was developed from subscale vessels, or if the full-scale COPV differs in configuration from the A-basis fiber vessels (e.g., cylinder vs. sphere), analytical validations in lieu of burst testing will be needed. These analyses must show that the A-basis fiber strength is valid for the full-scale COPV or that the A-basis allowable must be adjusted to account for differences between the full-scale COPV and the A-basis vessels. These data should be used to establish ultimate strength for the fiber/resin system.

The A-basis allowables should be calculated per the procedures in MIL-HDBK-17 (Ref. 15) and should include the test results from at least two lots of material unless all of the vessels are produced from the same lot. The results from production vessels of different configurations and subscale pressure vessels may be pooled.

A change in the resin system should require testing of a minimum of three subscale and/or full-scale vessels. The population of the mean delivered strength using the new resin system should be compared to the original delivered strength. The populations are considered equivalent if the variances and means pass the tests of equality (i.e., Levene's test and the F-test) as described in MIL-HDBK-17.

7.1.2 Guidelines for Generation of Composite Material Allowables

7.1.2.1 Composite Material Allowables Generated Using Full-scale Specimens

Many equally valid approaches can be used to provide ultimate strength design allowables. The approach selected should be justified with a supporting rationale. Examples of several approaches are given below. Other approaches not specifically identified may also be used.

1. A preferred approach is to test a sufficient number of full-scale pressure vessels of the production configuration. Testing of 30 vessels is recommended when a new yarn or resin is used, but fewer may be tested if relevant historical information exists. The results from production vessels of different configurations may be pooled where appropriate. Thickness, wrap patterns, size, and other relevant factors should be considered in pooling the data.
2. Strands impregnated with the production resin may be conducted to establish the variability in yarn strength within and between batches. Several production pressure vessels may be burst and the results used to establish average burst strength and delivered fiber stress. The results from analysis of variability of the strand tests may be applied to the average burst

strength to establish the design allowable. This approach is not universally endorsed but has been used.

3. Historically established design allowables may be used for new COPV design and validated by burst tests of two or more production vessels. There are a variety of valid approaches that can be used when a change is made to a yarn or resin for a production-qualified system. Approaches 1 through 3 above can be used for this purpose. Often a reduced test program can be justified by knowledge of the chemistry and/or properties of the resin or yarn and their similarity to those used on a previously qualified COPV. Examples of such approaches that have been used are described below. Technically supportable options other than those described may be used.

4. When the resin or any of the components used to make a resin or the yarn are changed, a test program should be conducted on full-scale COPVs. A preferred approach is to test a sufficient number of COPVs so that the techniques in MIL-HDBK-17 can be applied to show that the mean strength and variance for the new resin are equal to or greater than those for the previously used resin. For the normal scatter of results, one can expect that between 10 and 20 COPVs would need to be tested.

5. When the resin or any of the components used to make a resin or the yarn is changed, a test program should be conducted on a minimum of three full-scale COPVs. The mean strength should be shown to be equal to or greater than that obtained with the previously used resin. A judgment is made based on the results as to whether the new COPV is acceptable or not. This approach is not as analytically rigorous as the approach in 4, above.

7.1.2.2 Composite Material Allowables Generated Using Subscale Specimens

Ideally, allowables for composite materials are generated by testing full-scale specimens, as the material allowables appear to be configuration dependent. However, this may not be economically feasible when the full-scale part is large. Subscale test specimens may be used, but care must be taken to assure that valid results are obtained.

Subscale test specimens must use the same fiber and resin materials as intended for the full-scale part and must maintain the same relation of helical and hoop fiber thickness. Since the same fiber must be used, and the tow cross-sectional area is not scalable, a subscale part with a smaller diameter must necessarily have either thinner or fewer layers than the full-scale part, or the burst pressure must be higher. These problems with scaling may cause the fiber strength allowable to be affected. Past testing has shown that as part diameter increases, the apparent fiber strength may decrease. If strength decreases on the full-scale part, and no correction is made, mission reliability and success may be affected. Past testing has also shown that as burst pressure increases, the apparent fiber strength may decrease. This is due in part to thick-wall effects, which are more pronounced in composite materials because their orthotropy ratio is higher than for metals.

Differences in the wall thickness and thickness-to-diameter ratios interact with other aspects of part design and manufacture. Winding times, cure rates, residual stresses, and local discontinuities such as fiber crossovers or band terminations cannot be fully scaled.

The closer the diameters of the full-scale part and the subscale specimen, the better the chances of having a valid fiber strength allowable. If economics favor use of a small subscale specimen for primary testing, the use of an intermediate subscale part might improve strength predictions for the full-scale part. For example, if 60 specimens were desired to establish an A-basis strength allowable, a 1/10-scale specimen might be appropriate. If a limited number (e.g., 3–6) of 1/2-scale specimens were also tested, the effects of diameter could be evaluated and projections made for the allowable on the full-scale part.

Cylindrical subscale parts that are shorter than the full-scale part are also useful. The cylinder section of the subscale part should be long enough to properly address dome-cylinder junction discontinuities and their dissipation. Closeness of the helical wind pattern (e.g., single-loop vs. multiloop closure) should also be considered.

Use of a spherical pressure vessel to develop allowable fiber strengths for a cylindrical pressure vessel, or vice versa, offers more challenges to establishing acceptable allowables for a full-scale part. Additional testing may be required to validate use of specimens of a different configuration.

Tubular specimens under tension or combined tension and internal pressure, flat specimens loaded in tension, or strand tensile specimens should not be used to establish fiber strength allowable for a pressure vessel. Edge effects, size effects, discontinuities at loading points, and differences in three-dimensional stress states limit their value in determining fiber strength allowable in a pressure vessel.

7.2 Stress-Rupture Life

7.2.1 Stress-Rupture Life Requirements

The following stress-rupture life requirements are recommended:

The COPV should be designed to meet the design life, taking into account the time it is under a sustained load. There should be no credible stress rupture failure modes based on stress rupture data for a predetermined probability of survival (PoS) value. Unless otherwise specified, the minimum PoS should be 0.999.

7.2.2 Guidelines for Stress-Rupture Life Verification

Verification that a COPV will survive the time it is at pressure should be determined from the analysis methods and material database provided in this section for three major classes of yarns that have been characterized:

Polyacrylonitrile (PAN)-based, intermediate-modulus graphite yarns;
Kevlar 49;
E or S glass.

7.2.2.1 Design Curves

Curves are given in Figures 7-1 through 7-3 (Ref. 16) for determining the allowable sustained load operating stress for a specified time at load using a PoS of 0.999. The time at pressure represents the sum of the time that the COPV is pressurized at or is above 60% of MEOP.

7.2.2.2 Determination of Stress-Rupture Life for Other Probability Values

For a PoS value higher than 0.999, new curves can be created through use of the two-parameter Weibull distribution equation below:

$$P(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}}$$

where $P(t)$ = probability of failure for a specified value of time (design life)
t = time in hours
α = Weibull shape factor
β = Weibull beta (characteristic life)

The values of α and β can be determined from the equations in Table 7-1. The equations can then be manipulated for various probabilities of survival values and plotted like Figures 7-1 through 7-3.

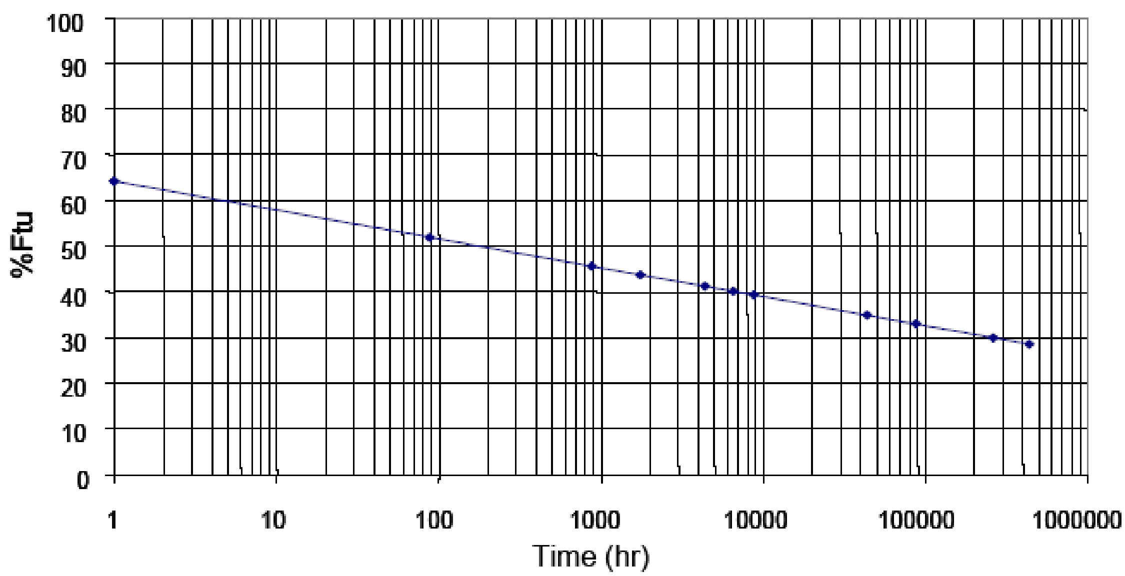


Figure 7-1. Sustained load design curve for COPVs with fiberglass (source: Ref. 16).

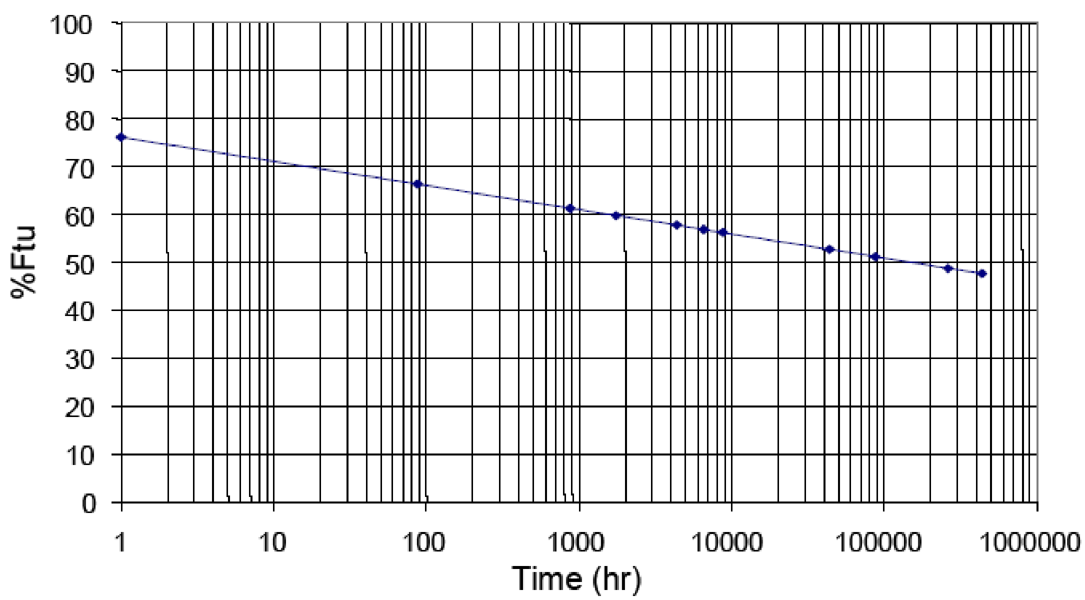


Figure 7-2. Sustained load design curve for COPVs with Kevlar fibers (source: Ref. 16).

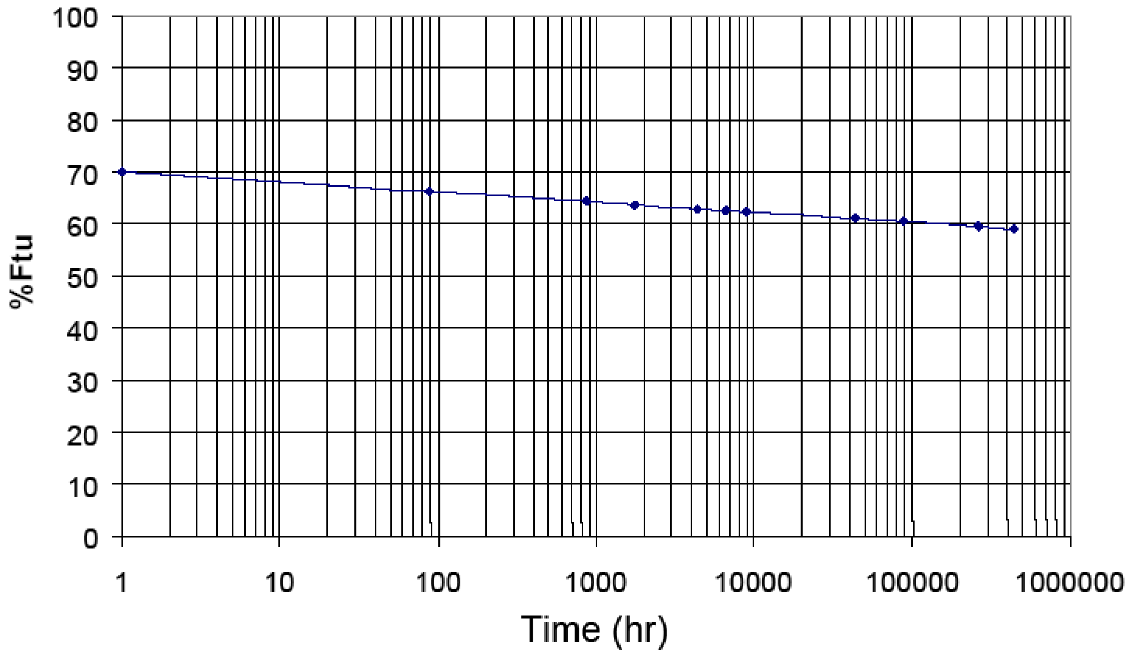


Figure 7-3. Sustained load design curve for COPVs with graphite fibers (source: Ref. 16).

Table 7-1. Lifetime Model Weibull Parameters (Source: Ref. 16)*

Composite System	**Shape Parameter**	**Scale Parameters**
Glass/epoxy	Alpha = 1.00	Beta = $(1.4 \times 10^{13})10^{[-0\ 158(\%ULT]a}$
Kevlar/epoxy	Alpha = 0.93	Beta = $(2.0 \times 10^{18})10^{[-0\ 198(\%ULT]}$
Graphite/epoxy	Alpha = 0.20	Beta = $(1.4 \times 10^{51})10^{[-0\ 515\%ULT]}$

* %ULT is the applied stress level as a percentage of the ultimate burst strength
(e.g., for applied stress level of 50% ultimate burst strength, %ULT = 50)

7.2.2.3 New Materials

New materials will require determination of stress-rupture behavior. Although long-term pressure testing of COPVs would be preferable, strand tests provide a conservative guideline for determination of stress-rupture behavior. A general approach for creating design curves from COPV data is outlined below.

In order to create a stress-rupture curve, data from COPV tests of a minimum of two load levels should be available. No fewer than three samples should be available at each load level. (Note: if more data exist or more samples are used, the results will be less conservative).

1. For each load level, the Weibull parameters from the equation in section 7.2.2.2 should be determined. The procedure below can be followed to determine the parameters:

    (a) A set of data is gathered that contains times to failure of different COPVs for several stress levels. Data at each stress level is then tabulated in increasing order and ranked (using a median rank table).

(b) After ranking the data, the data at each stress level is plotted individually on Weibull paper as a function of rank. A best-fit line is drawn through the data (visually, or using a fitting technique such as linear regression). Alpha and beta values for each stress level are determined directly from the chart.

(c) From charts created for each stress level, the beta values are plotted as a function of stress level. A semi-log plot of scale parameter vs. %FTU should be used to provide a linear function. An equation for the function is determined and used to determine the beta value for the system (see those in Table 7-1). To determine the system shape parameter, the lowest alpha value should be chosen.

2. Use the Weibull equation provided above to generate a lifetime curve. Curves should be plotted on a lognormal scale.

7.3 Impact Damage Control

Impact damage control is an important element in the design, fabrication, testing, and operation of COPVs used in RLVs and affect safety of the crew and passengers.

7.3.1 Impact Damage Control Requirements

The following set of impact damage control requirements is recommended:

Impact damage that may degrade the performance of the COPV below the minimum strength requirements should be prevented. An impact damage control plan is mandatory.

For impact damage mitigation, a minimum of one of the following approaches should be adapted:

(a) Impact Damage Protection/Indication;

(b) Damage Tolerance Demonstration

These two approaches are described below.

An impact damaged COPV requires procurement agency Material Review Board (MRB) approval prior to use.

7.3.1.1 Impact Damage Control Plan (ICP)

The ICP should document the threat analysis and procedures that mitigate these threats. The impact threat analysis should document the conditions (source and magnitude of threat and state of pressurization of the COPV) under which impact damage can occur. The ICP should delineate all potentially damaging events and investigate mitigating procedures from the point of time when the COPV reinforcing matrix is cured to the end of service life.

7.3.1.1.1 Approach A – Impact Damage Protection/Indication

Protective covers should provide isolation from impact damage events. Protective covers should be used when the COPV has not demonstrated sufficient strength after an impact damage incident that is consistent with the worst-case credible impact threat. The following requirements should apply for protective covers and/or indicators:

Protective Covers

The effectiveness of protector covers should be demonstrated by test.

Protective covers or standoffs that isolate the vessel are required when personnel will be exposed to pressurized COPVs having stored energy levels in excess of 14,240 ft-lbf or containing hazardous fluids. They should be designed to completely protect the COPV under the worst credible impact threat. They should allow transmission of less than 5 ft-lbf (6.8 joules) of energy or reduce the transmitted energy to a level not to exceed one-half that demonstrated as acceptable by pressurized damage tolerance or residual strength testing.

Protective covers should not be removed until the latest practical time prior to launch or during other critical operations requiring cover removal.

Indicators

When protective covers are not used, or the indicators are placed between the protective cover and the COPV, the effectiveness of the indicators to provide positive evidence of a mechanical damage event less than or equal to the demonstrated residual strength capability of the unprotected COPV should be demonstrated by test. If residual strength testing of the COPV is not performed, the indicators should be capable of detecting a 5 ft-lbf (6.8-joule) impact with a 0.5-in.-(13-mm)-diameter steel hemispherical tup impactor.

When indicators are placed outside of the protective cover, the effectiveness of the indicator to provide a positive evidence of impact in excess of the cover isolation capability should be demonstrated by test.

The use of indicators as the sole means of mitigating threats for pressurized COPVs during personnel workaround is prohibited.

7.3.1.1.2 Approach B – Damage Tolerance Demonstration

Mechanical damage tolerance demonstration is an alternative to, or complementary with, mechanical damage covers to satisfy the requirements for damage control.

Impact Damage Tolerance Demonstration

Impact damage should be induced using a drop-type impactor and a 0.5-in.-(13-mm)-diameter, steel hemispherical tup. A pendulum-type arrangement may be used if an analysis substantiates energy and momentum levels equivalent to a drop test. The minimum energy level should be the greater of the worst-case threat, or visual damage threshold (VDT). After inducing damage to the COPV, verification of the capability to satisfy the strength requirements should be demonstrated by test. The damage should be induced in the most damage-critical condition (e.g., pressurized vs. unpressurized) and location.

7.3.2 Guidelines for Mechanical Damage Control

COPVs are known to be susceptible to mechanical damage resulting from handling, tool drop impacts, or impacts from other objects. For some COPVs, tests have shown that their burst-strength-after-impact (BAI) at the visual damage threshold (VDT) impact energy level is lower than the specified design burst pressure of the vessel. These test results are shown in Appendix B. For this reason, S-081 requires mechanical-damage control throughout all stages of the COPV, i.e., manufacturing, testing, transportation, ground handling, system integration, and launch. For COPVs used in RLVs, which have multimission usage requirements, refilling and retest should be considered.

The purpose of mechanical-damage control for a COPV is to establish procedures that:

1. Identify the mechanical damage approach that will be implemented for the COPV intended usage;
2. Define methods for detecting and evaluating the potential mechanical damage incidents by the material review board (MRB); and
3. Identify the approach for assessing the burst strength of a COPV following a mechanical damage incident.

Among the mechanical damage, impact could be the most detrimental damage to COPVs made of carbon fibers/epoxy composite materials. The following sections concentrate on the impact damage control.

7.3.2.1 Overview of Impact-Damage Control Process

Impact-damage control should be implemented at every stage throughout the life of the COPV beginning at the manufacturing plant and through the various test and integration stages leading up to launch. An overview of various paths that can be taken in an impact damage control process has been developed (Ref. 17).

Figure 7-4 illustrates that impact-damage control can be implemented using at least one of three basic methodologies:

1) By procedure only;
2) By using an impact protection system;
3) By demonstrating impact damage tolerance.

The first method, by procedure only, requires 100% quality assurance (QA) surveillance to ensure that no damage has occurred to the COPV. QA personnel must be trained and certified in impact damage susceptibility of COPVs and in methods of performing NDE, including visual inspections. To apply this methodology, prior approval should be obtained from the procuring agency and the safety organization that has the judiciary for launch.

The second method is to use an impact protection system capable of absorbing the indentation and deflection damage from all potential impact scenarios in the impact threat environment. This also requires the impact indicator to positively identify that an impact damage event has occurred. This method requires QA surveillance only during the installation and removal of the COPV protective covers.

The third method is to demonstrate that a COPV, after being subjected to impact damage at the VDT level, still has a BAI equal to or higher than its design burst pressure.

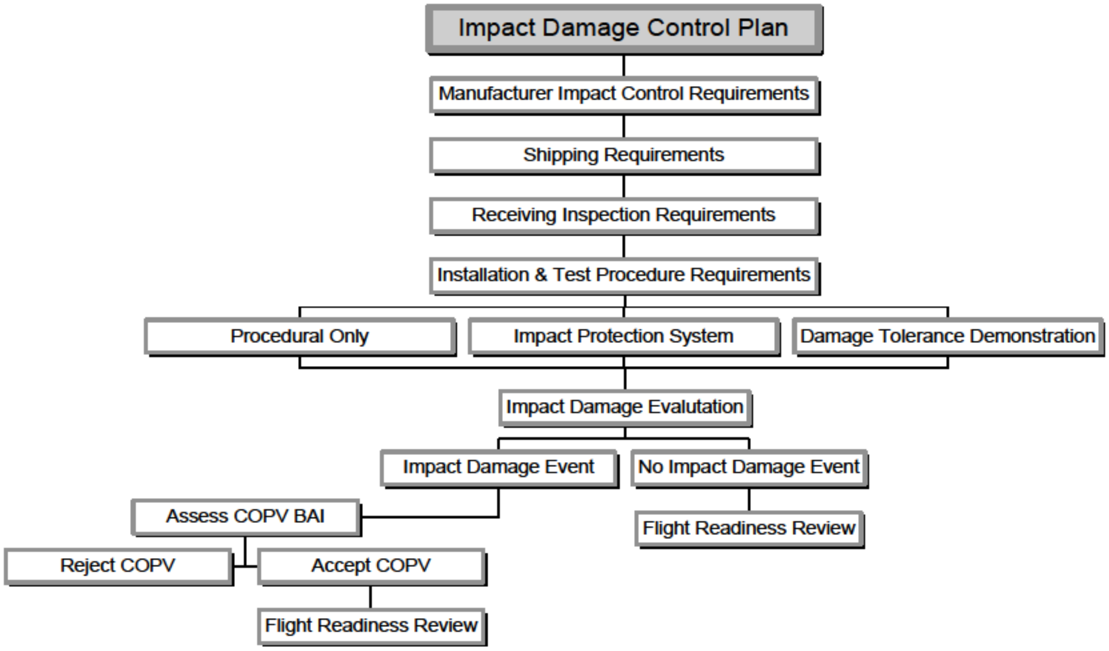


Figure 7-4. Impact damage control process options (Ref.17).

7.3.2.2 Impact Protection System

7.3.2.3 Impact Damage Tolerance Demonstration

Impact damage is generally caused by improper handling or impacts associated with work about or above the COPV. Most plausible damage events affecting the encapsulating composite overwrap of the COPV should be assessed by evaluating its BAI. The following approaches for an impact damage tolerance demonstration are based on this type of assessment program.

1. An assessment should be made that includes credible impact conditions, impact locations, pressurization conditions, and environmental conditions. The assessment should identify drop heights, velocities of potential impacts, masses of objects, and the shape for each object. The threat analysis of the post-fabrication handling damage of the COPV design performed in the system analysis should be used for damage tolerance assessment. This assessment may make use of similarity data from prior programs using similar metal liner materials, metal liner diameter-to-thickness ratio, composite materials, composite thickness, and laminate design, or of development test data for the COPV. Impact damage effects assessment results conducted by a government/ industry team are shown in Appendix B.

2. After the completion of the assessment, the results should be used to establish the visual damage threshold (VDT) of a specific COPV design. This can be done by assessment of impact events on the COPV at the preselected locations and impact conditions. After the impact event, the visual inspection is then performed. Inspection should be performed by inspector(s) with formal training in inspecting impact damages on COPVs. Multiple impacts can be applied on the same test article. Full-scale COPV(s) should be used to avoid scaling effect concerns. Multiple impacts at different conditions can be applied on the same test article provided a minimum distance is kept. As the rule of thumb, the minimum distance should be ten times the impactor size.

3. After the establishment of VDT for a specific COPV design, an undamaged COPV should be used as the test article for impact damage tolerance demonstration. The VDT level impact should then be applied on the test article at the most critical location at the worst-case pressure level. The stress analysis results should be used to select the locations. Visual inspections should be performed to verify that the impact is indeed not visible or barely visible. After the visual inspection, the test article should be placed in the burst test chamber and pressurized to failure. The pressure at burst is the burst-strength-after-impact (BAI).

4. The success criterion for the impact damage tolerance test is that BAI $\geq$ DBF $\times$ MEOP. The impact damage tolerance can be demonstrated by a standard test sequence, identified below:

   (a) A 10 in. drop of the COPV so that one of its surfaces strikes a wood table. For cylindrical COPVs drops should occur onto the cylindrical section and onto the closure dome section. For spherical bottles, the impact region should be at the minimum thickness zone of the overwrap, the highest-stressed region of the composite, and the location of the final tie-off.

   (b) A 6 in. drop onto polar boss regions (after removal of porting features, including transition tubes).

   (c) A 35 ft-lb impact by a 1/2 in. tup at the location of greatest damage sensitivity of the vessel: For cylindrical COPVs, this includes the cylindrical section in the region of final tie-off and the highest-stress region on the closure dome. For spherical COPVs, the vessel will be impacted at the location of the final tie-off, and at the predicted failure location for an undamaged vessel, based on the results of the stress analysis.

   (d) Inspect the vessel by the methods defined by the manufacturer at vessel acceptance. Record all detectable conditions.

   (e) Subject the vessel to the following pressure test:

      - Fill at a rate less than or equal to the maximum fill flow rate to 110% of MEOP;
      - Hold for a minimum of 10 minutes at 110% MEOP;
      - Fill at a rate less than or equal to maximum fill flow rate to proof pressure;
      - Hold at proof pressure for 5 minutes minimum;
      - Fill at a rate less than or equal to maximum fill flow rate to minimum design burst pressure;
      - Hold at minimum burst for 30 seconds; and
      - Pressurize to rupture.
      - A pressure transducer should be mounted as close as practically possible to the vessel inlet port during pressure testing. Document the results, including description of initiation location and deviation of behavior from undamaged burst test specimen.

7.4 COPV NDE Techniques

7.4.1 COPV NDE Requirements

The following NDE requirements are recommended:

The selected NDE techniques for the metal liner should be according to Section 4.6.2 of ANSI/AIAA S-080. Inspection should be performed before overwrapping with composite materials. At a minimum after overwrapping, the NDE technique should consist of a detailed visual inspection by a trained inspector at the points defined by the damage control plan. Other inspection techniques should be used when warranted.

The NDI procedures for COPVs should be documented and based on using multiple NDE methods when appropriate to perform survey inspections or diagnostic inspections. The flaw detection capability of each selected NDE technique or combination of NDE techniques as applied to the composite overwrap should be based on similarity data from prior test programs. Where these data are not available or are not sufficiently extensive to provide reliable results, the flaw detection capability, under production operational inspection conditions, should be determined experimentally. It should then be demonstrated by tests approved by the procuring agency on representative material product form, thickness, design configuration, and damage source articles. Assessment of composite overwrap damage tolerance that uses quantitative NDE data should follow the procedure outlined in Section 4.2.10 of ANSI/AIAA S-081 to determine the accept/reject condition for each type of damage source.

7.4.2 NDE Techniques for Metal Liners

The NDE techniques selected for metallic liners should have the capability to determine the size, geometry, location, and orientation of flaws and defects. If multiple flaws exist, the technique should be able to determine the location of each with respect to the other and the distance between them. The NDE technique(s) selected should be able to differentiate flaws in the range from tight cracks to spherical voids. Two or more NDE methods should be used in cases where the item cannot be adequately examined by only one method. The liner of a COPV should be inspected before overwrapping with composite materials and after the sizing process.

Commonly used NDE techniques for detecting cracks or crack-like flaws in metallic hardware items or COPV liners include: eddy current, dye penetrant, magnetic particle, radiography, and ultrasound. The flaw detection capability of NDE techniques has been established in the NASA fracture control requirements document (Ref. 10) and was presented in Table 6-1. If NDE techniques selected for inspections are not included in that table, the selected technique should be capable of detecting allowable initial flaw size corresponding to a 90% probability of detection at a 95% confidence level with the flaw shape (a/2c) ranging from 0.1 to 0.5 for surface flaws and (a/c) ranging from 0.2 to 1.0 for corner cracks.

Inspection data in the form of flaw histories should be maintained throughout the life of the pressure vessel. These data should be reviewed periodically and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept, and structural configuration. The results of this assessment should form the basis of any required corrective action.

7.4.3 NDE Techniques for Composite Materials

The NDE techniques selected for inspecting the composite overwrap of COPVs should follow an approved procedure. An NDE evaluation program has identified the state-of-the-art methods that can be used to detect damage of COPVs. The results are in Appendix C. These methods include visual inspection, thermography, shearography, ultrasound, and eddy current. Advantages and disadvantages are identified for each method. However, there is no statistical evaluation to determine their probability of detection, as has been established for NDE techniques used for metallic hardware items.

Other techniques may be developed or refined for the application to COPV inspections. For impact damage, visual inspection is an acceptable technique. However, the inspector should have adequate training to inspect impact damage.

7.5 LBB Demonstration

7.5.1 LBB Requirements

The following LBB requirements are recommended:

When Leak-Before-Burst (LBB) is chosen as the COPV design approach, only the regions of the COPV liner that are covered by the composite are required to exhibit an LBB failure mode at MEOP. Specifically, the areas of a boss, which are not covered by the composite and remain elastic at all pressures in the service life should be designed for safe-life or per this section for LBB. The shear region of the boss located under the composite where the internal pressure can shear the boss through the opening of the composite should be excluded from both safe-life and LBB design requirements.

When the liner remains elastic at all pressures and/or loads in the service life, linear elastic fracture mechanics should be used to show that both of the following conditions are satisfied:

(a) An initial part-through crack (surface flaw) with a shape (a/2c) ranging from 0.1 to 0.5 should not fail (cause catastrophic burst) at any stress intensity factor applied during the service life ($K < K_{Ie}$ at all times), and

(b) This part-through crack should grow through the wall of the pressure vessel liner to become a through crack with a length equal to ten times the wall thickness, thereby causing the contents to leak out before catastrophic failure (burst) can occur.

LBB Demonstration Testing

When the strain in the liner is elastic at MEOP, LBB should be demonstrated by analysis, test, or similarity. When the strain in the liner exceeds the strain at which linear elastic fracture mechanics is applicable at MEOP, the LBB failure mode should be demonstrated by test or similarity. LBB verification should establish that all critical areas exhibit LBB.

LBB Demonstration Using Coupons

Testing should be conducted on uniaxial coupons that duplicate the materials (wrought materials, weld joints, or heat-affected zones), processes, and the thickness of the COPV liner. The coupons should start with a surface crack and meet the requirements for validity of an appropriate method from a published standard of a recognized standards institute for a crack whose length equals ten times the coupon thickness. Cycle loads should be applied to the test specimen to generate a peak strain corresponding to the strain at MEOP, as determined by analysis. LBB failure mode is demonstrated if the surface crack breaks through the thickness and grows to a length that is ten times the coupon thickness without causing the coupon to fracture.

LBB Demonstration Using a COPV

A COPV representative of the flight COPV (liner material, processing, thickness, configuration, and reinforcing composite stiffness and thickness) should be used. Surface cracks should be put into the liner only at locations and orientations that are most critical to LBB response. An inert fluid should be used to pressurize the COPV. Pressure cycles should be applied to the COPV, with the upper pressure equal to MEOP. LBB failure mode is demonstrated if the crack causes the pressure to leak from the COPV at MEOP before catastrophic failure occurs.

7.5.2 Guidelines for LBB Demonstration

For metallic pressure vessels and elastic response metal liners of COPVs, the LBB demonstration can be done by either a fracture mechanics based analysis or by LBB test. For plastic response COPV metal liners, test is the only acceptable method to demonstrate LBB failure mode

The reason to select the "10 × thickness" requirement for MPVs was discussed in Section 6. For the metal liner of a COPV, the same crack length requirement is adapted in S-081. When metallic material is in the elastic range, linear elastic fracture mechanics should be used in the failure mode predictions, i.e., $K(10t) < K_c$, where K_c is the plane stress fracture toughness of the material.

For plastically responsive metal liners of COPVs, the LBB demonstration should be conducted at the strain levels determined by elastic-plastic analysis at the undamaged state. If a full-scale COPV is to be used, the initial flaws are better fabricated on the outer surface of the liner using an electric discharge machining (EDM) process before it is overwrapped with composite materials. However, if there is a large enough opening in the port area for the EDM process, the initial flaws can be fabricated on the inner surface of the liner after the liner is overwrapped.

The initial size and shape of the EDM prefabricated flaws should be carefully selected so that fatigue precracking cycles can be applied in order to initiate the sharp fatigue crack at the tip of the EDM notch. If a full-scale COPV is used as the test specimen, crack growth should be closely monitored. After the part-through crack penetrates the thickness of the COPV, leakage may have developed and the internal pressure of the vessel may drop very fast. Before the crack length reaches to ten times the wall thickness, internal pressure should be maintained by pumping the vessel with more test fluid. When the pump rate increases to its maximum allowable and still cannot overcome the leakage, the test should be discontinued. Under this condition, LBB is considered to have been demonstrated.

7.6 Acceptance Proof Testing

7.6.1 Acceptance Proof Testing Requirements

The following acceptance proof testing requirements are recommended:

The COPV should be proof tested to a minimum pressure of:

$$P = (1 + \text{Burst Factor})/2 \times \text{MEOP (for a burst factor less than 2.0)} \quad \text{or}$$
$$= 1.5 \times \text{MEOP (for a burst factor equal to or greater than 2.0).}$$

Unless otherwise stated, the duration of the proof test should be sufficient to verify pressure stability. The COPV should not leak, rupture, or experience detrimental deformation during proof testing. Proof-test fluids should be compatible with the structural materials used in the COPV and not pose a hazard to test personnel. The proof test fixture should emulate the structural response or reaction loads of the flight mounting where COPV mounting induces axial or radial restrictions on the pressure-driven expansion of the vessel. The temperature should be consistent with the critical use temperature, or test pressures should be suitably adjusted to account for worst-case temperature effects on static strength and/or fracture toughness.

7.6.2 Guidelines for COPV Acceptance Proof Testing

7.6.2.1 Autofrettage/Sizing Operation

In the metal-lined COPV manufacturing processes, there is a very important step after the wrapping of the composite material system to the metal liner. That is the autofrettage/sizing pressure cycle.

The term *autofrettage*, meaning self-hooping, was originally applied to artillery pieces such as cannons. It is a mechanism used to improve fatigue characteristics of the metal liner. The maximum pressure in the autofrettage pressure cycle is usually high so that the liner will experience plastic deformation (gross yielding). When the pressure is subsequently reduced to zero, residual compressive stresses in the yield region of the liner are induced. Therefore, the liner's yielding zone will see less stress during the subsequent pressure cycles with maximum pressures lower than the autofrettage pressure.

7.6.2.2 Workmanship Screening

Every pressurized hardware item should be proof pressure tested. An objective for performing proof testing is to provide evidence of satisfactory workmanship so that the tested hardware item can sustain the subsequent service loads, pressure, temperatures, and environments. The temperature should be consistent with the critical use temperature, or test pressures should be suitably adjusted to account for temperature effects on strength and fracture toughness.

For COPVs whose liners carry only a small portion of the pressure loads (< 10%), the ratio of the proof pressure to the average burst pressure of the COPV should be kept below 0.80. The average burst pressure value should be determined from the development test program.

Proof test fluids should be compatible with the structural materials. If such compatibility data are not available, testing should be conducted to demonstrate that the proposed test fluid does not impose any deleterious effects on the hardware.

Accept/reject criteria should be formulated prior to acceptance proof test. At a minimum, the hardware item should not experience measurable pressure decay as a result of leakage or rupture, or experience detrimental deformation during the acceptance proof test, and should successfully complete subsequent post-proof test NDI. At a minimum, post-proof NDI should be conducted in the weld region because defects there tend to extend during the proof test. Particularly essential for a metallic pressure vessel (MPV) or a metallic pressurized structure (MPS) is that the stress in the weld be in the plasticity range during the proof test.

7.7 COPV Leak Test

7.7.1 COPV Leak Requirements

The COPV should be leak tested after pressure cycling to verify the compliance with the requirements.

7.7.2 Guidelines for COPV Leak Test

Leak test should be performed after proof-pressure test. During the leak check, the pressure level should be maintained at MEOP for a minimum of 30 minutes after the background has stabilized if the test leak rate is 1×10^{-6} SCC/sec or higher. If the test leak rate is less than 1×10^{-6} SSC/sec (e.g., 1×10^{-7} SCC/sec), the pressure level should be maintained at MEOP for longer than 30 minutes.

If hydrocarbon contaminants such as oils or other liquids are introduced into the tank prior to leak test, the tank should be cleaned and dried prior to leak test to prevent corruption of the leak test due to leak signature scavenging by the contaminant. In any case, at a minimum, the vessel should be dried before leak testing. Required end item cleanliness is not necessary to conduct a valid leak test.

Response time characterization of the test apparatus should be performed and documented prior to conducting a leak test and should be repeated if the test chamber or fixture is subjected to substantive rework or refurbishment. The response time of the system should be used to establish the required hold time of the vessel at the test pressure.

The temperature of the vessel should be monitored during fill and venting to ensure that safe operational limits are not exceeded. Both the metallic end fittings (if present) and the composite overwrap should be monitored. The maximum and minimum temperatures experienced by these elements during leak test should be recorded.

The leak test should be conducted using a certified and a calibrated system. System calibration and sensor instrumentation calibration are both required. Calibration should be done at a minimum of one decade below the maximum specified leak rate for the vessel using a standard rate.

Mechanical fitting isolation from the vessel leak signature is permissible if it is shown that isolation of fittings does not result in scavenging of the leak signature from the vessel.

7.8 Additional Topics

7.8.1 Development Testing

The purposes of development testing are:

1. Reduce qualification program risk;
2. Supplement the rationale for hardware certification, as applicable;
3. Validate adequate safe-life margin;
4. Demonstrate adequate fatigue life; and
5. Demonstrate damage tolerance capability.

Development tests should be conducted on every new hardware design before commitment to production. Success criteria should be formulated prior to tests. These requirements also apply to existing designs that have significant modifications.

The number and types of tests required to demonstrate proof of concept/design will depend on the design principles employed, with an acceptable degree of confidence. The following are pertinent guidelines:

1. Selection of instrumentation for the purpose of characterizing or quantifying a critical parameter should be based on high confidence and probability of detection (PoD) and the ability to define/characterize the essential properties. The instrumentation types and their locations should be determined based on the results of the stress analysis in addition to considerations in regard to selection of the instrument. The instrumentation selected and test plans developed should provide sufficient data to determine the accept/reject basis.
2. The test sequence should be designed to measure vessel parameters due to, at a minimum, worst case singular/combined effects resulting from proof cycles, life cycle, and expected operating environments.
3. The test sequence should be designed to account for combinations of loads, levels and duration of loads, pressures, and environmental effects. For example, the test sequence for a COPV design should include employment of techniques to evaluate the effects and changes in characteristics of the metal liner and composite overwrap properties resulting from the tests.

4. Effects of external loads caused by supports should be evaluated. The supporting structure for the pressure vessel should be a replica or structure that accurately replicates the loading scenario on the flight vehicle.
5. Parameters should be evaluated and conservative limits provided to address effects of thermal and mechanical shock (due to pressure cycling, variations in flow, system configuration changes, and external factors) on the PV using full-scale test articles affixed to a replica of the support structure to be used.
6. The test sequences should be suitable for demonstrating that the design requirements can be met.

7.8.2 Qualification by Similarity

There are situations in which pressurized hardware items can be qualified by similarity. Usually, this provision should apply to one-of-a-kind hardware items, off-the-shelf items, or a small production program where the test article is expensive and the schedule is compressed. This provision can be applied to the entire qualification test program or a portion of it. Recommended conditions for conducting a reduced qualification burst test were proposed by J. P. Lewis (Ref. 18) and are shown in Table 7-2. To meet the conditions set in this table, temperature effects should be assessed.

Table 7-2. Recommended Conditions for Qualification by Similarity (Source: Ref. 18)

Deviation from Previously Qualified Vessel	**LBB Demonstration**[1]	**Safe-Life Demonstration**	**Dynamic/Static Load Test**	**Pressure Cycle Test**	**Burst Test**
New Design[2]	X	X	X	X	X
Increased Length			X	X	X
Decreased Burst Factor/Increase MEOP	X	X	X		X
Decreased Diameter			X[3]		
Increased Diameter	X	X	X	X	X
Increased Composite Thickness			X[3]		
Decreased Composite Thickness	X	X	X	X	X
Increased Liner Thickness	X	X	X[3]		
Decreased Liner Thickness	X	X	X	X	X
Change Proof Pressure	X	X		X	X
Chance Autofrettage Pressure	X	X		X	X
Change Mounting		X[4]	X	X[4]	X

Notes:

- X Denotes Required Test
- LBB failure mode may be qualified by similarity when both the liner and vessel thickness and strain at MEOP are less than or equal to those of previously qualified vessels.
- Changes in head shape, liner material, liner heat treatment, composite materials, wrap pattern, and boss dimensions (including boss taper) are considered to be a new design.
- A delta-qualification test may be required if analysis of the dynamic environments, stiffness, natural frequency, and mass indicate higher stresses for new (modified) designs.
- Test is required only if new mounting constrains the tank shell expansion more than mounting in qualification test.

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Appendix A
Fatigue Analysis Methods

Currently, several analytical methods are being used in the aerospace industry for the evaluation of fatigue failure resistance capability (durability or fatigue life) of structures and other hardware. All methods require similar information:

- Load and environment spectrum,
- Identification of candidate locations for fatigue failure,
- Stresses or strains at the candidate locations,
- Fatigue analysis methodology and corresponding material characteristics.

Assumptions must be made or known about the loadings to which the structure or other hardware items will be subjected during their lifetime. Development of load spectrum, including the magnitudes and numbers of cycles, is a special field in itself. Often, the dynamic responses of a structure are needed. Determination of locations in the structure in which fatigue may be an important consideration is usually based on experiences with similar structures, even if made of other materials. In the absence of such experience, joints, notches, abrupt changes in geometry, and areas of localized loads and stresses are candidate locations for fatigue crack initiations, and thus candidate locations for fatigue failure. Once the load spectrum is established and the candidate fatigue failure locations are determined, the stress (strain) spectrum can be derived through appropriate stress analysis methods, such as a classic strength-of-materials approach or by finite element modeling techniques. Choosing an appropriate fatigue analysis methodology is based on the type of information needed. The material data used in the analysis are dictated by the analysis method. In this section, state-of-the-art fatigue analysis methods are briefly introduced.

A.1 Stress-Life (S-N) Method

The stress-life method uses fatigue data plotted on an S-N diagram (curve). On a typical S-N curve, the stress measurement, σ, is plotted as the ordinate (vertical axis) and the life, N, as the abscissa (horizontal axis). The stress term can be the maximum stress, σ_{max}, or the stress range, $\Delta\sigma = \sigma_{max} - \sigma_{min}$, where σ_{min} is the minimum stress of a stress cycle. Three types of loading spectra exist: constant amplitude, variable amplitude, and random. The degree of complexity of the fatigue life prediction depends largely on the type of stress spectrum.

A.1.1 Constant Amplitude Loading

The simplest case uses a straight-line S-N curve, such as the log-log plot shown in Figure A-1, to estimate the fatigue life of a simple panel (un-notched) under zero-tension constant amplitude loading. The curve can be expressed mathematically by the equation

$$\sigma = AN^{-1/m} \tag{A-1}$$

or

$$N = A\sigma^{-m} \tag{A-2}$$

where σ = stress

m = slope of the S-N curve

A = material constant, defining the interception of the S-N curve at the ordinate for one cycle

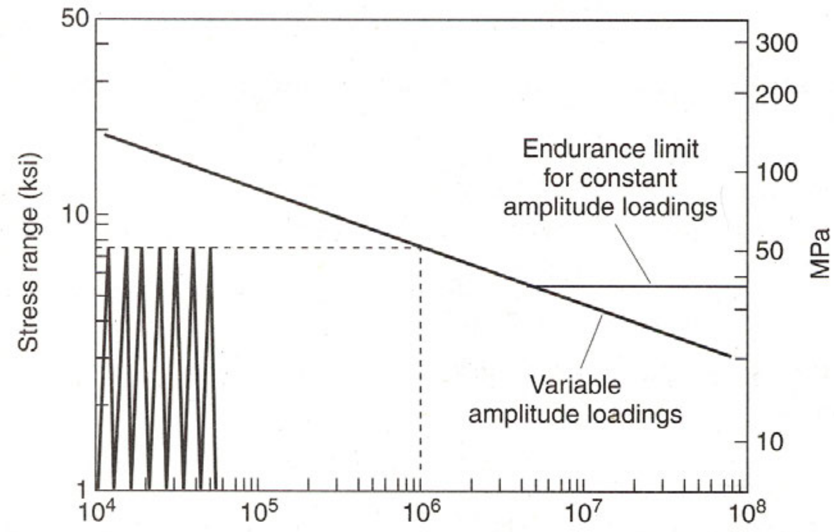

Figure A-1. Design of longitudinal butt weld with constant-amplitude loading using aluminum association category B (Ref. A-1).

If the maximum stress, σ_{max}, is known for a structure under constant amplitude loading, the number of cycles until structural failure can be predicted. The predicted number of cycles, N_p, is then compared with the known service life, N_s, also in terms of cycles. A life factor, $\lambda = 4$, is usually applied to the predicted life, N_p, when the mean S-N curve is used. The fatigue life criteria is satisfied if

$$\frac{N_p}{\lambda} = \frac{N_p}{4} \geq N_s \tag{A-3}$$

Other statistical treatments can be applied to determine the S-N curve. For example, data can be drawn with 99% probability of survival with 95% confidence level to form A-basis S-N data.

Sometimes, the stress range, $\Delta\sigma$, is used to plot the S-N curve. In this case, the predicted number of cycles is

$$N_p = A(\Delta\sigma)^{-m} \tag{A-4}$$

The design stress range, $(\Delta\sigma)_d$, will be

$$(\Delta\sigma)_d = AN^{-1/m} \tag{A-5}$$

A.1.2 Variable Amplitude Loading

For loading at two or more stress levels, Miner's Rule (or the Miner-Palmgren law) is commonly used (Ref. A-2). Miner's Rule is a linear cumulative damage scheme that states failure will occur when

$$\sum \left(n_i / N_i \right) = 1 \tag{A-6}$$

where n_i = number of cycles of the *i*th stress range

N_i = number of cycles to failure at the *i*th stress range

In a structure subjected to loadings at several different levels, failure is predicted to occur when the summation of the number of cycles at each load level divided by the average life to failure at that load level equals 1.

The Miner-Palmgren rule is an approximation and cannot be expected to be 100% accurate. To improve the accuracy, factors that affect the fatigue life should be considered, such as stress ratio, $R = \sigma_{min}/\sigma_{max}$, temperature, and corrosive environments. Other effects such as structure size and notches should also be considered, as appropriate.

For unwelded material and mechanically fastened joints, the effect of mean stress or stress ratio should be factored into the design. Under cyclic loading, tensile stresses cause fatigue crack initiation and propagation; compressive stresses tend to impede initiation and propagation. Thus, for a given stress range, the life decreases as the mean stress increases. A modified Goodman diagram is often used as the method of combining constant-amplitude S-N curves for different stress ratios in one plot. As shown in Figure A-2, maximum stresses relating to the selected lives are plotted on the vertical axis and the corresponding minimum stresses on the horizontal axis. Accordingly, R = 0 results are shown on the central, vertical axis. Stress-life relationships for other stress ratios are also plotted on straight lines. If the stress ratio of a design loading does not match given data, the appropriate value can be determined from the interpolated curves.

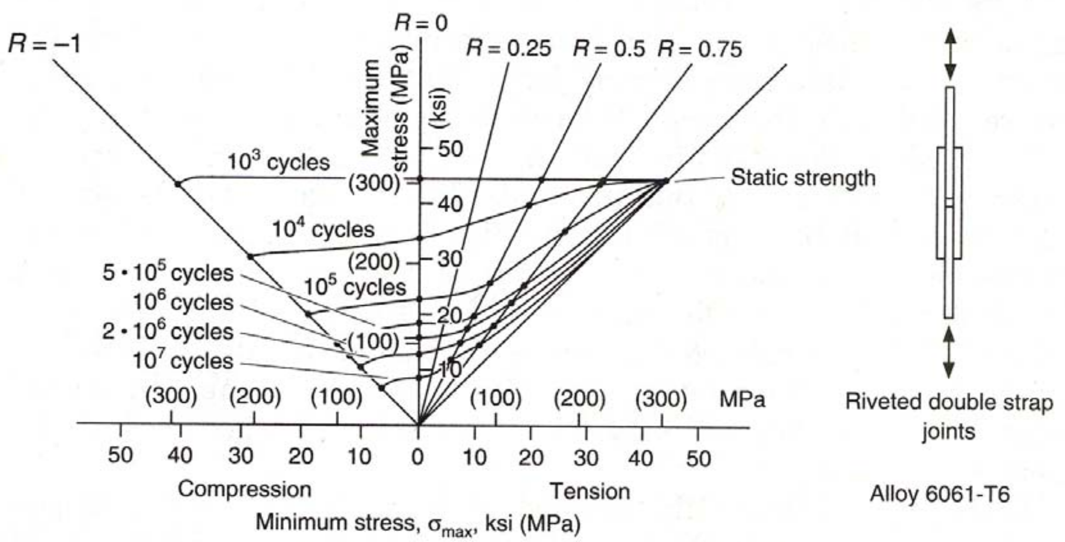

Figure A-2. Modified Goodman diagram.

Effects of temperature and corrosive environment depend largely on the material used. In general, temperature and corrosive environment have profound effects on the fatigue life of metals. For example, the fatigue strength of aluminum alloys and joints is higher at low temperatures. Corrosion severe enough to cause pitting of the material surface may lower the fatigue strength. Therefore, it is extremely important to use the fatigue data generated from correct temperature and corrosive environment. Structure size effects are also potentially large and must be taken into account.

A.1.3 Equivalent Stress Approach

An alternative method for calculating damage from variable amplitude loading has been introduced by the Aluminum Association (Ref. A-3). This method uses an equivalent stress range, $(\Delta\sigma)_{eq}$, and Miner's rule. For a stress range spectrum:

$$\alpha_i N_T = n_i \tag{A-7}$$

where α_i = percentage of total cycles in the spectrum of the *i*th stress range

N_T = total number of cycles in load spectrum

Miner's Rule may then transformed to

$$\sum \alpha_i \left(N_T / N_i \right) = 1 \tag{A-8}$$

where N_i = number of cycles to failure of the *i*th stress range

The life equation may be rewritten as

$$N_i = A(\Delta\sigma_i)^{-m} \tag{A-9}$$

where A = constant defining the S-N curve

m = slope of the S-N curve

$\Delta\sigma_i$ = *i*th stress range in the spectrum

Miner's rule may be rewritten as

$$\sum \alpha_i \left[\frac{N_T}{A(\Delta\sigma_i)^{-m}} \right] = 1 \tag{A-10}$$

If the total number of cycles is represented by

$$N_T = A(\Delta\sigma_{eq})^{-m} \tag{A-11}$$

then Miner's Rule will become

$$\sum \alpha_i (\Delta\sigma_{eq})^{-m} \left[\frac{1}{(\Delta\sigma_i)^{-m}} \right] = 1 \tag{A-12}$$

Solving for equivalent stress range, $\Delta\sigma_{eq}$:

$$\Delta\sigma_{eq} = \left[\sum \alpha_i (\Delta\sigma_i)^m \right]^{1/m} \tag{A-13}$$

A.2 Strain-Life (ε-N) Method

For structures with notches, the behavior of material at the root of the notch is best considered in terms of strain. This is the basis of the low cycle fatigue analysis approach, also referred to as the notch-strain analysis technique. The methodology combines material behavior and local strains in critical regions of a part for life prediction based on the initiation of a crack. The primary assumption is that no initial crack exists in the part *a priori*. For structures containing initial flaws, crack growth analysis using fracture mechanics principles are appropriate.

The strain-life method starts with a strain-life (ε-N) curve as shown in Figure A-3. Data for this curve were obtained from cyclic tension-compression tests of smooth specimens in laboratory air. The ordinate of Figure A-3 is one-half of the strain range, $\Delta\varepsilon$, which is the difference between maximum strain (ε_{max}) and minimum strain (ε_{min}). The abscissa is the number of reversals or twice the number of cycles. The curve takes into account elastic ($\Delta\varepsilon_e$) and inelastic or plastic ($\Delta\varepsilon_p$) strain contributions, and contains an approximation for the effects of mean strain. The equation of the strain-life curve follows:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} \qquad \text{(A-14)}$$

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f - \sigma_m)(2N_f)^b}{E} + \varepsilon_f (2N_f)^c$$

where $\Delta\varepsilon/2$ = one-half of the strain range

σ_f = fatigue-strength coefficient

σ_m = mean stress

$2N_f$ = numbers of reversals to failure

b = fatigue-strength exponent

ε_f = fatigue-ductility coefficient

c = fatigue-ductility exponent

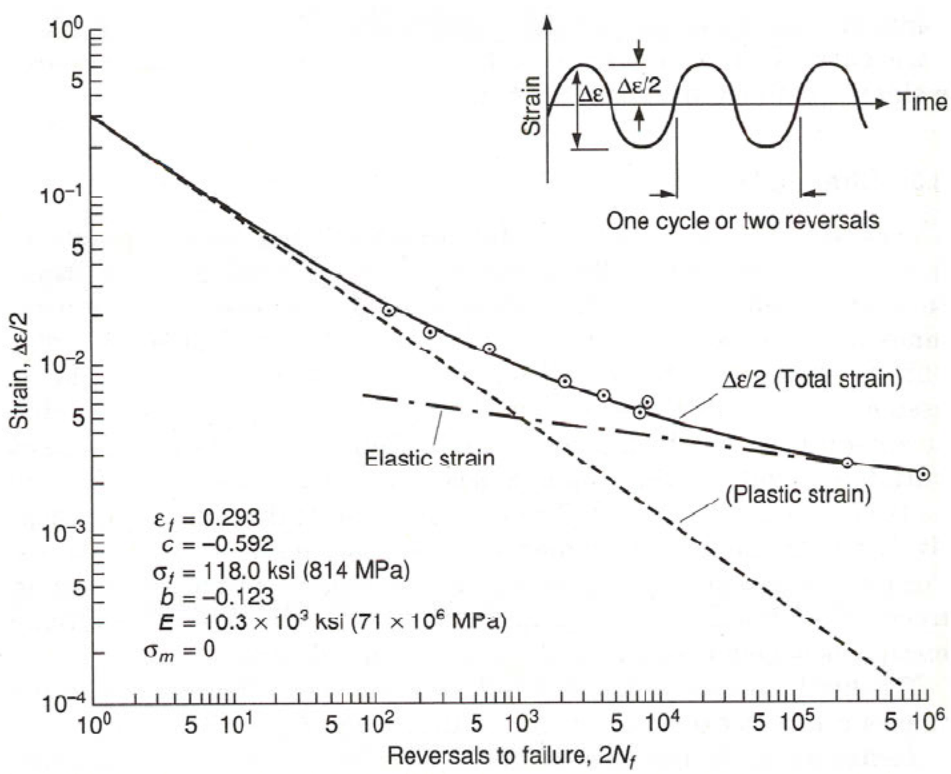

Figure A-3. Strain vs. reversals to failure for aluminum alloy 5182-0.

The straight-line elastic behavior can be transformed to

$$\frac{\Delta\sigma}{2} = \sigma_f (2N_f)^b \qquad \text{(A-15)}$$

This is Basquin's Equation (Ref. A-4). The exponent "b" ranges from –0.06 to –0.14, with –0.1 as a representative value. Basquin's Equation can be used to estimate the equivalent life, N_2, under stress constant amplitude stress, σ_2, if the life, N_1, for stress, σ_1, is known.

$$\frac{N_2}{N_1} = \left(\frac{\sigma_1}{\sigma_2}\right)^{-1/b} \tag{A-16}$$

The relation between plastic strain and life is

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f \left(2N_f\right)^c \tag{A-17}$$

This is the Manson-Coffin Equation (Refs. A-5 and A-6). The exponent "c" ranges from –0.5 to –0.7, with –0.6 as a representative value.

An important part of the analysis is calculation of local strains at critical areas of the structure due to the applied loads. For complex structures and other hardware items, finite element analysis (FEA) is widely used with good results. Biaxial and triaxial stresses and strains will often be calculated by FEA in the critical area. However, Neuber's rule has been used to estimate the strains from external loads rather accurately. Neuber's rule can be expressed as

$$\Delta\sigma \cdot \Delta\varepsilon = \frac{\left(K_f \Delta\sigma_n\right)^2}{E} \tag{A-18}$$

where $\Delta\sigma$ = local stress range at notch root

$\Delta\varepsilon$ = local strain range at notch root

$\Delta\sigma_n$ = nominal stress range in the specimen

E = modulus of elasticity

K_f = fatigue factor

The fatigue factor, K_f, is the ratio of fatigue strength in a smooth specimen to fatigue strength in a notched specimen, both at the same long life. An estimate of K_f may use the following equation:

$$K_f = 1.0 + \frac{K_t - 1}{1 + \sqrt{\rho / r}} \tag{A-19}$$

where K_t = elastic stress-concentration factor

ρ = material constant

r = radius of notch

Because this value of K_f is approximate, values from tests should be used when available. The right side of the equation has a constant value for a given nominal stress on the member. Thus, the strain at which the product of the local stress range and the local strain range equals that constant value is the local strain needed for life prediction. This strain can be obtained by trial and error from the formula or by intersection of the curve from Neuber's rule and the cyclic stress-strain curve. This local strain and the curve from Figure A-3 provide an estimate of life to initiate cracking for a particular material.

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Appendix B
Linear Elastic Fracture Mechanics (LEFM) Methodology

Linear elastic fracture mechanics (LEFM) methodology is based on a principle that assumes that fracture behavior for a homogeneous and isotropic body loaded within the linear elastic region is dominated by the crack tip stress intensity factor, K. For a panel uniformly loaded in elastic tensile stress, σ, that contains a centrally located through-crack with a length 2a, the stress intensity factor can be expressed as

$$\boldsymbol{K} = \beta\sigma\sqrt{\pi a}$$

where β = geometry correction factor.

This is the so-called opening mode (Mode I) stress intensity factor, or K_I (Figure B-1). Besides Mode I, a crack can extend in two other independent modes: shearing (or sliding) mode, Mode II, and tearing (or antiplane) mode, Mode III. K used without a subscript (I, II, or III) usually refers to Mode I.

For a pressure vessel (PV), the opening mode, Mode I, is usually the predominant fracture mode. Many methods have been used to derive stress intensity factors. Among them, the finite element method is the most popular, especially for three-dimensional (3-D) cases. Quite a few stress intensity factor handbooks have been published that document various K factors with different crack geometries and loading conditions (Refs. B-1 through B-3).

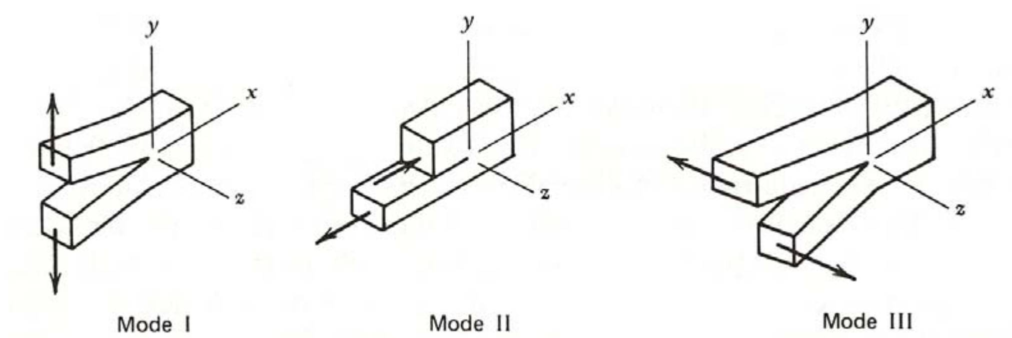


Figure B-1. Three modes of crack extension.

For a cracked panel under cyclic elastic tensile loading, many investigators have observed that the stress intensity factor range, ΔK, is the controlling parameter. In terms of K, the stress intensity factor range can be expressed as

$$\Delta K = K_{max} - K_{min}$$

where K_{max} and K_{min} are the maximum and minimum stress intensity factors, respectively. They correspond to the maximum stress (σ_{max}) and minimum stress (σ_{min}) in a stress cycle.

More than 30 fatigue crack growth rate models have been proposed since the mid 20th century. The most popular is the “Paris Law” (Ref. B-4). In the early 1960s, Paris observed that for an aluminum alloy, the da/dN versus ΔK plotted in log-log scale is a straight line. He then proposed his famous Paris Law, which can be expressed as

$$da/dN = C(\Delta K)^n$$

where n = the slope of the straight line

C = intersection of the straight line with the vertical axis with ΔK = 1 ksi√in.

Fatigue crack growth life can be determined by solving the first-order differential equation. Several integration techniques can be used to provide a solution to this type of differential equation:

- Direct integration
- Runge-Kutta integration technique
- Taylor series approximation method
- Liner approximation scheme

Of the above methods, the direct integration method is the simplest. However, β is a function of crack size “a” and other geometry, and the application is limited to β = 1 condition.

For a center crack, with a length 2a contained in a wide plate subject to zero-tension constant amplitude cyclic loading, the stress intensity factor range can be expressed as

$$\Delta \boldsymbol{K} = \beta(\sigma_{max} - \sigma_{min})\sqrt{\pi a} = \sigma_{max}(1-R)\sqrt{\pi a},$$

where the geometry correction factor β = 1 and $\sigma_{min} = 0$.

The crack growth rate is then

$$da/dN = C\left[\sigma_{max}(1-R)\sqrt{\pi a}\right]^n$$

Through direct integration, the crack growth life is

$$\Delta N = \frac{2}{C(2-n)(1-R)^n\left(\sigma_{max}\sqrt{\pi}\right)^n}\left[(a_f)^{1-n/2} - (a_o)^{1-n/2}\right],$$

where a_o and a_f are the initial and final crack sizes, respectively.

The final crack size is usually calculated by using the fracture toughness, K_c, of the material’s fracture property:

$$a_{cr} = \frac{\boldsymbol{K}_c^2}{\pi\sigma_{max}^2} = 0.32\left(\frac{\boldsymbol{K}_c}{\sigma_{max}}\right)^2$$

When the initial crack is known (usually determined by nondestructive inspection), the number of cycles that will be required for the crack to grow from a_o to a_{cr} can be calculated.

B.1 Example

A 16-in.-diameter helium bottle made of a titanium alloy (Ti-6Al-4V, STA) has a 0.15 in. membrane wall thickness and 0.25-in.-thick weld. The planned use of this helium bottle is in an RLV, so it will therefore be refilled many times during its service life. The maximum expected operating pressure (MEOP) of this bottle is 4,000 psig. In order to achieve safe operation and mission success, a decision is made to use a fracture control approach to determine the inspection interval after the bottle is put into use. Assume that the weld region is the most critical location on this pressure vessel. No cracks or crack-like defects were found. In the fracture mechanics safe-life calculation, the initial flaw size, based on probability of detection (PoD) established for a standard dye penetrant, is: crack depth a = 0.75 in. and crack length 2c = 0.15 in. for a semicircular surface flaw. The initial flaw for the weld region is a = c = 0.7t = 0.175 in. From Ref. B-5, the fracture toughness and crack growth rate constants for this titanium alloy (Ti-6Al-4V, GTA weld) are: $K_{Ie} = 50$ ksi√in, $K_{Ic} = 42$ ksi√in, C = 2.28×10^{-9} in./cyc^{-9}, and n = 3.

Use a simple formula to estimate the operating stress:

$$\sigma_{op} = PR/2t = 4000\times8/2\times0.25 = 64 \text{ ksi.}$$

The final crack size can be calculated as

$$a_{cr} = 0.32\ (K_{Ie}/\sigma_{max})^2 = 0.32\ (50/64)^2 = 0.195 \text{ in.}$$

The total number of cycles that will be needed to fail the cracked weld region is

$$\left(N_f - 0\right) = \frac{2}{\left(2.28\text{x}10^{-9}\right)\left(2-3\right)\left(64\sqrt{\pi}\right)^3}\left[\left(0.195\right)^{1-3/2} - \left(0.175\right)^{1-3/2}\right]$$

$$N = \frac{2}{\left(2.28\text{x}10^{-9}\right)\left(\text{-}1\right)\left(1442897\right)}\left[0.195^{-0.5} - 0.175^{-0.5}\right]$$

$$N = -600\cdot\left(2.26 - 2.39\right) = 78\text{cycles}$$

The inspection level can be set to 19 MEOP pressure cycles.

B.2 Crack Growth Software

Since 1970s, many crack growth computer codes have been developed. These include CRACKS (Ref. B-6), CRKGRO (Ref. B-7), FLAGRO (Ref. B-8), and recently, NASGRO (Ref. B-5). These software codes have different features but can all be used to perform crack growth safe-life analysis. For space-flight pressure vessels, the current trend is to use NASGRO since it contains a vast array of stress intensity factors for crack models that represent pressure vessel geometries. It also contains a large fracture and crack-growth rate (da/dN) database for materials used in fabricating pressure vessels including titanium, corrosion-resistant steel (CRES), Inconel, etc.

B.3 References

B-1. G. C. Sih, ed., *Mechanics of Fracture,* Noordhoof International Publishing, Leyden, 1973.

B-2. H. Tada, P. C. Paris, and G. R. Irwin, *The Stress Analysis of Cracks Handbook,* Del Research Corp., St. Louis, Missouri, 1973.

B-3. D. P. Rooke and D. J. Cartwright, *Compendium of Stress Intensity Factors,* 1976.

B-4. P. C. Paris, M. P. Gomes, and W. P. Anderson, "A Rational Analytic Theory of Fatigue," *Trends in Engineering*, vol. 13, 1961.

B-5. *Fatigue Crack Growth Computer Program, NASA/FLAGRO*, JSC-22267, NASA-Johnson Space Center, Houston, TX, 1985.

B-6. R. M. Engle, "CRACKS, A Fortran IV Digital Computer Program for Crack Propagation Analysis,"AFFDL-TR-70-107, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, 1970.

B-7. J. B. Chang, M. Szamossi, and K-W Liu, "A Users Manual for a Detailed Level Fatigue Crack-Growth Analysis Computer Code - The CRKGRO Program," AFWAL-TR-81-3093, 1981.

B-8. T. Hu, "*Advanced Crack Propagation Predicative Analysis Computer Program, FLAGRO 4*," Rockwell International, SOD 79-0280, 1980.

Appendix C
A COPV Impact Damage Effects Assessment Study

An experimental program was conducted in the mid-1990s to study the effect of impact on COPVs (Ref. C-1). The study involved measurement of the burst strength after impact (BAI) as a function of the following variables:

- Impact energy level
- Impactor geometry
- Vessel geometry/size
- Impact location
- Internal pressure level during impact
- Pressure media (gas or liquid)

The following sections briefly describe the highlights of the test program and a summary of the test results as documented in Ref. C-2.

C.1 Test Specimens

Four types of flight-qualified COPVs, shown in Figure C-1, were selected as impact damage test specimens. The characteristics of these COPVs are as follows:

- **Type 1:** 19 in. nominal outer diameter sphere made of cryo-stretched 301 corrosion-resistant steel (CRES) overwrapped with Hercules IM-7 carbon fiber and epoxy resin. The 301 CRES liner had a thickness of 0.035 in., and the composite overwrap thickness was 0.18 in. This COPV design was qualified for the high pressurant tank used for helium storage for the propulsion subsystem of a spacecraft. The maximum expected operating pressure (MEOP) was 4,500 psi.
- **Type 2:** 10.25 in. nominal outer diameter sphere made of 5086 aluminum alloy overwrapped with Amoco T-40 carbon fiber and epoxy resin. The aluminum liner had a 0.05 in. thickness, and the composite overwrap thickness was 0.18 in. This COPV was qualified for a space program with a 5,000 psi MEOP. It has been requalified to a 6,000 psi MEOP.
- **Type 3:** 6.6-in.-diameter cylinder, 20 in. long. Its liner is made of 6061-T62 aluminum alloy. The overwrap material was Toray T-1000 carbon fiber and epoxy resin. In the cylinder section, the liner thickness was 0.035 in. and overwrap thickness was 0.109 in. The vessel was qualified for a launch vehicle with a 5,000 psi MEOP. It has been requalified for a 6,000 psi MEOP.
- **Type 4:** 13-in.-diameter cylinder, 25 in. long. The liner and the composite materials were identical to Type 3. The thickness of the liner was 0.041 in. in the cylindrical section, and overwrap thickness was 0.15 in.

C.2 Test Procedure

An instrumented mechanical impact tester (IMIT) was used to perform the impact test. The real-time response of the impactor and the test article was recorded using semiconductor strain gauges. An I-beam frame supported the IMIT to allow for placement of the tested COPVs under the impactor tup (Figure C-2). After each impact, the fluid in the vessel was discharged, and the vessel was inspected visually by three trained inspectors. In addition, nondestructive inspection (NDI) techniques, which included infrared (IR) thermography, eddy current, and ultrasonic A-scan, were used to determine how well the impact could be detected by a particular NDI technique. Furthermore, acoustic emission sensors were employed during some of the pressurization. After the inspections, the vessel was pressurized in the test chamber until burst. The burst pressure was identified as BAI of that specific COPV.

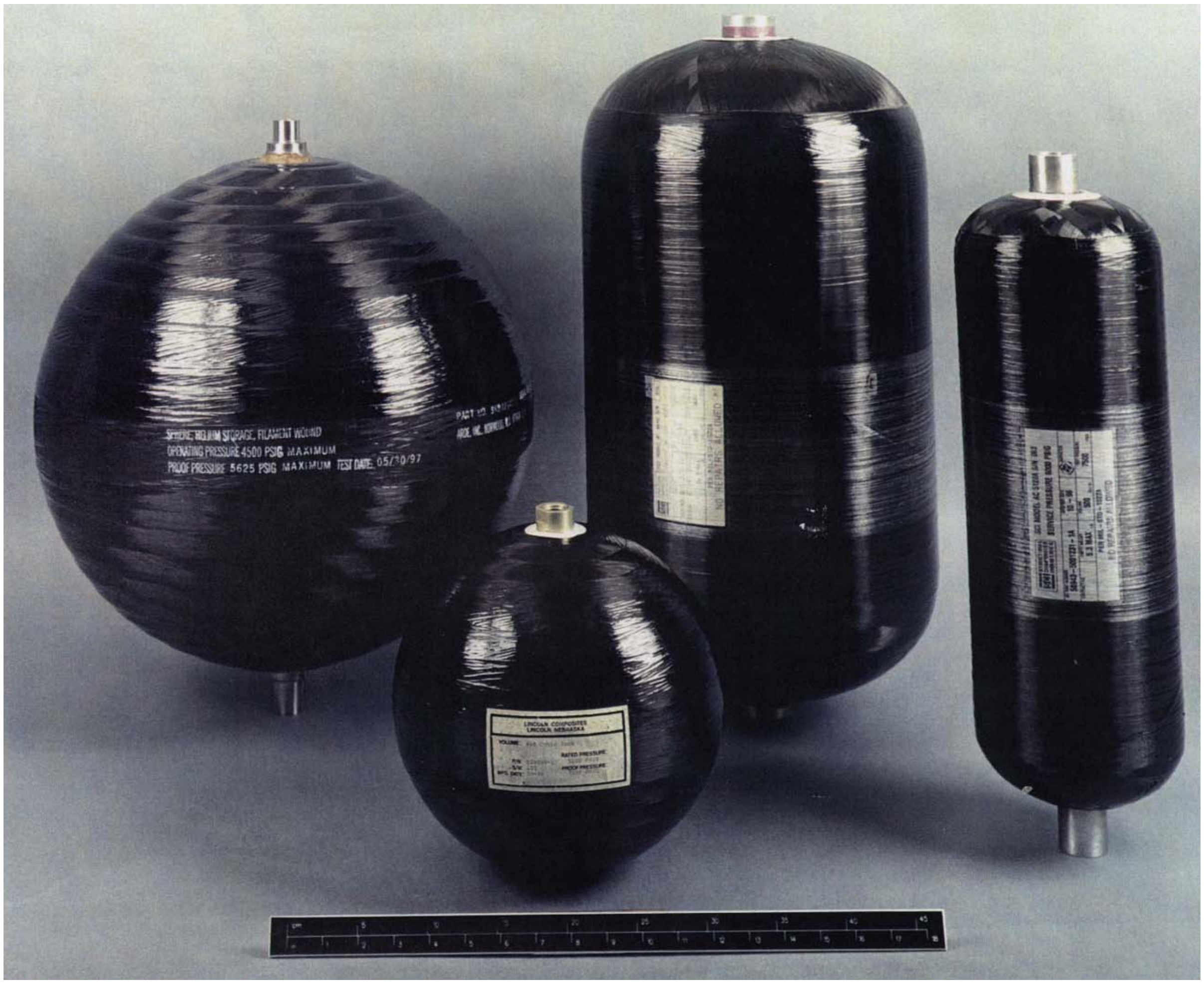


Figure C-1. Four types of flight-qualified COPVs used as impact test specimens.

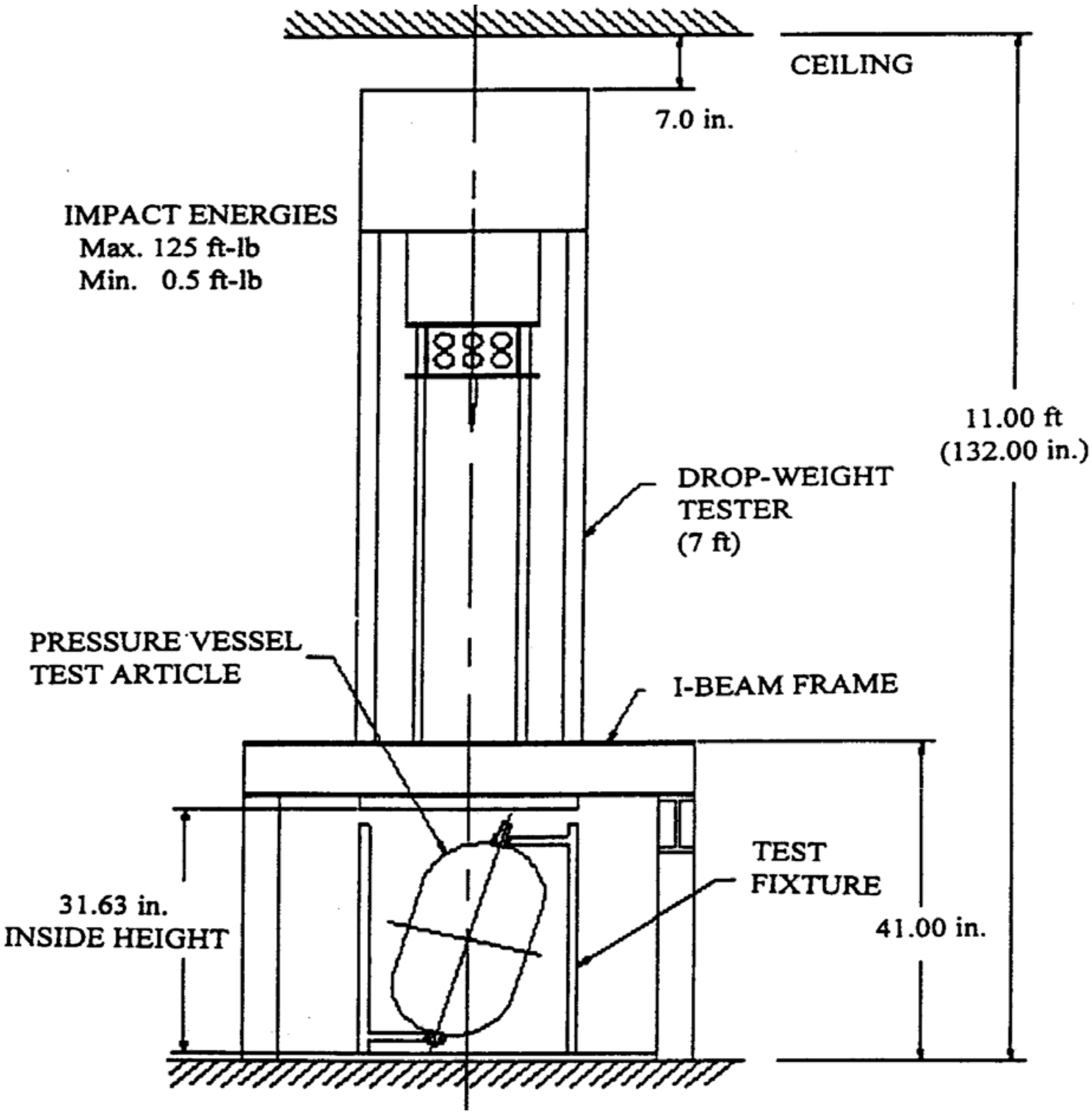


Figure C-2. Instrumented mechanical impact tester.

C.3 Impact Test Results

The impact damage test results show the effect of various conditions and variables on the BAIs of the tested COPVs (Tables C-1 and C-2). For the small spherical (Type 2) COPVs, the applied impact energy (IE) level ranged from 25 to 50 ft-lb, with the majority of the test conducted at 35 ft-lb. Since in one test case (S/N B-64), the damage generated by an IE of 35 ft-lb was not detected visually by all three inspectors, this IE level was determined as the visible damage threshold (VDT) for Type 2 COPVs. The test results shown in Table C-1 indicate that, in general, the BAI decreases as the IE increases. The results also show that the BAI has a higher scatter for a specific IE level when compared to the undamaged vessels, which have only a ±3% variation. The internal pressure levels showed significant effects on the BAIs. When the vessels were pressurized at their MEOP level of 6,000 psi at the time of impact, BAIs were higher than those impacted while empty. The choice of pressurizing fluid—either gas or water—had no significant effect on the BAI.

Table C-1. Impact Test Results for Small Spherical (Type 2) COPVs

S/N	IE (ft-lb)	Pressure Level at Impact (psi) and Test Fluid	BAI (psi)	Degradation %	Remarks
B-77	25	Empty	11,106	>Baseline[1]	Impact @ boss/0.5 in. tup
B-58	25	Empty	10,243	3	Norm Condition[2]
B-57	35	Empty	8,415	21	Norm Condition
B-61	35	Empty	7,136	7	Norm Condition
B-62	35	Empty	7,816	26	Impact @ Equator/0.5 in. tup
B-69	35	Empty	8,920	16	1 in. tup
B-64	35	Empty	8,707	18	1 in. tup, not detected[3]
B-73	35	Empty	9,294	12	1 in. tup
B-72	35	Empty	9,826	7	Norm Condition/50 cyc
B-70	35	Empty	8,159	21	Norm Condition/50 cyc
B-84	35	Empty	9,113	14	Norm Condition/50 cyc
B-85	35	Empty	8,894	16	Norm Condition
B-68	35	6,500(W)	9,924	12	Norm Condition
B-96	35	6,500(W)	9,914	6	Norm Condition
B-71	35	6,500(W)	9,417	11	Norm Condition
B-81	35	6,500(G)	10,496	1	Norm Condition
B-82	35	6,500(G)	9,294	12	Norm Condition
B-83	35	6,500(G)	9,396	11	Norm Condition
B-86	40	Empty	8,145	23	Norm Condition
B-78	50	Empty	7,399	30	Norm Condition

Nomenclature: BAI = burst strength after impact, IE = impact energy level, W = water, G = N_2 gas.
Notes: 1. Baseline burst strength of undamaged Type 2 vessels is 10,600 psi
2. Impacted at membrane section with 0.5 in. tup
3. One of three inspectors missed damage visually

Table C-2 shows the impact test results for the small cylindrical (Type 3) COPVs; the applied IE level ranged from 5 to 20 ft-lb. The VDT was determined to be 15 ft-lb. At this IE level, the inspectors could not visually detect the damage sites of two test specimens (S/N S-08 and S-04).

The most significant result is the effect of the pressure level during impact. When the cylindrical vessels were pressurized with water to 0.5 × MEOP (3,000 psi) and then subjected to an impact at the VDT level (15 ft-lb), the BAIs (except S-08) were higher than for those vessels that were empty during impact. The trend was the same (except B-72) as that observed in the small spherical COPV tests. However, when the water pressure was increased to MEOP (6,000 psi), the BAIs decreased significantly. The BAI decreased even more when gas, instead of water, was used as the pressurizing fluid. At the VDT level (15 ft-lb), one test specimen (S/N S-33) exploded 0.7 sec after impact. The end result of the failure for this COPV was dramatic. Many loose pieces were found in the test chamber. Figure C-3 shows the vessel remnants from the impact test. Compared to the results of a typical hydraulic burst test (Figure C-4), the potential threat of an unexpected impact is obvious even for an unprotected COPV charged with gas during transportation or ground handling.

Table C-2. Impact Test Results for Small Cylindrical (Type 3) COPVs

S/N	IE (ft-lb)	Pressure Level at Impact (psi) and Test Fluid	BAI (psi)	Degradation, %	Remarks
S-18	5	Empty	9,800	8[1]	Norm condition[2]
S-06	10	Empty	8,884	17	Norm condition
S-32	15	Empty	8,246	23	Norm condition
S-05	15	Empty	8,377	22	Norm condition
S-30	15	Empty	9,257	14	Norm condition
S-08	15	Empty	10,123	5	Impact @ transition[3]
S-20	20	Empty	7,764	28	Norm condition
S-13	15	3,000[4](W)	9,892	8	Norm condition
S-09	15	3,000(W)	9,425	12	Norm condition
S-04	15	3,000(W)	9,776	9	Norm condition[6]
S-29	15	6,000[5](W)	7,510	30	Norm condition
S-22	15	6,000(W)	7,950	26	Norm condition
S-38	15	6,000(W)	8,877	17	Norm condition
S-31	15	6,000(G)	7,569	29	Norm condition
S-33	15	6,000(G)	N/A	N/A	Exploded[7]
S-37	15	6,000(G)	7,724	28	Norm condition

Nomenclature: BAI = burst strength after impact, IE = impact energy level, W = water, G = N_2 gas

Notes:
1. Baseline burst strength of undamaged Type 3 vessels is 10,700 psi
2. Impact at membrane section with a 0.5 in. tup
3. One of three inspectors missed damage visually
4. 0.5 × MEOP
5. MEOP
6. All three inspectors missed damage visually

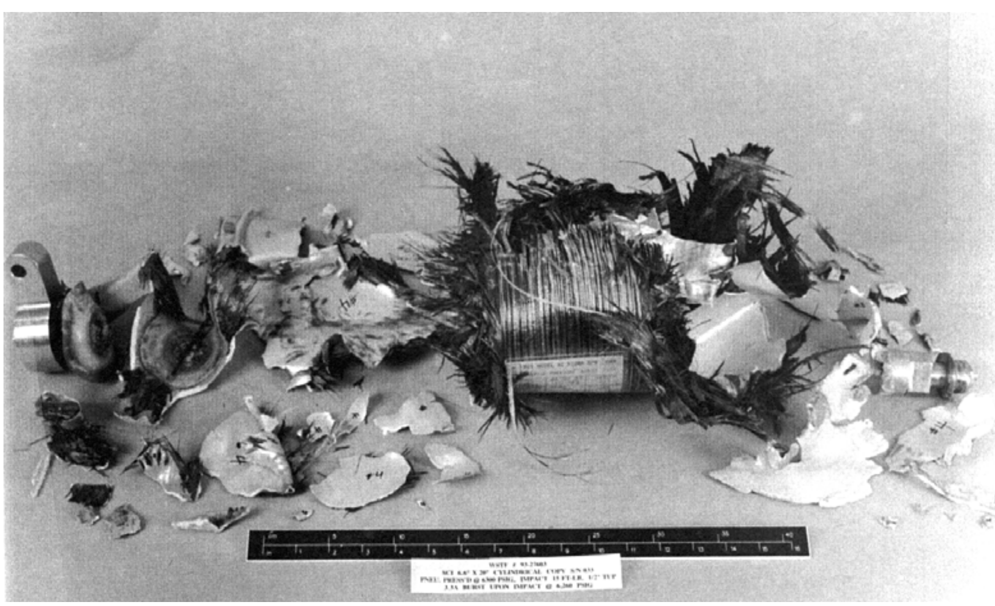


Figure C-3. Vessel remnants after pneumatic burst at impact, test S-33.

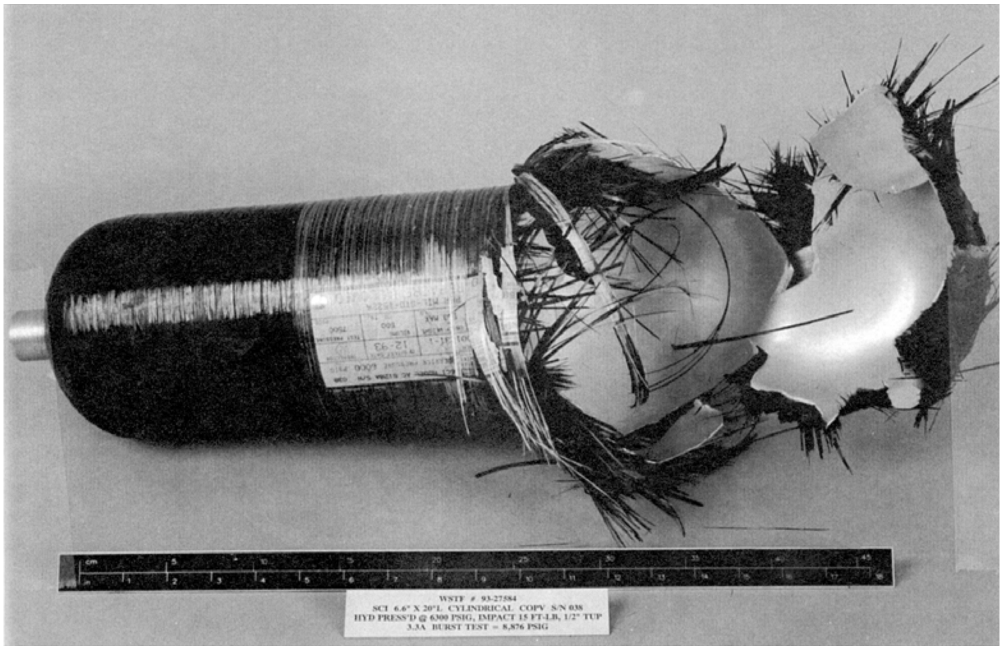


Figure C-4. A typical COPV remnant after hydroburst test.

Impact test results for the large spherical (Type 1) and cylindrical (Type 4) COPVs are shown in Table C-3. Compared to the BAI of the small COPVs, the large cylindrical COPVs degraded more as the IE increased.

Table C-3. Impact Test Results for Large Cylindrical and Spherical COPVs

S/N	IE (ft-lb)	Pressure Level at Impact (psi) and Test Fluid	BAI (psi)	Degradation %	Remarks
Type 1					
93-27681	35	Empty	7,054	3.1[1]	Impact @Membrane-Inlet
93-27671	65	Empty	7,256	0.3	Impact @Membrane-Boss
93-27672	100	Empty	6,256	14.1	Impact @Membrane-Boss
93-27673	100	4,725[2](G)	6,228	14.5	Impact @Membrane-Boss
93-27674	100	4,725(G)	5,987	17.8	Impact @Membrane-Inlet
93-27675	100	4,725(G)	6,235	14.6	Impact @Membrane-Inlet
93-27676	100	Empty	6,294	13.5	Impact @Membrane-Inlet
93-27679	100	Empty	6,941	4.7	Impact @Membrane-Inlet
Type 4					
93-27662	25	Empty	7,263	7.5[3]	Impact @ Hoop[4]
93-27666	30	Empty	6,482	17.4	Impact @ Hoop
93-27661	35	Empty	5,953	24.2	Impact @ Hoop
93-27668	35	Empty	5,126	34.7	Impact @ Dome
93-27670	35	Empty	5,309	32.4	Impact @ Dome
93-27663	35	4,500[5](W)	5,877	25.1	Impact @ Hoop
93-27664	35	4,500(W)	6,010	23.4	Impact @ Hoop
93-27660	50	Empty	5,401	31.2	Impact @ Hoop
93-27658	65	Empty	5,185	33.9	Impact @ Hoop

Nomenclature: BAI = burst strength after impact, IE = impact energy level, W = water, G = N_2 gas

Notes:
1. Baseline burst strength of undamaged Type 1 vessels is 7,280 psi
2. 1.05 × MEOP
3. Baseline burst strength of undamaged Type 4 vessels is 7,774 psi
4. Impact with a 0.5 in. tup
5. MEOP

C.4 Significant Findings

The following are the significant findings from this study:

- The test results revealed high variability in strength degradation as a function of influencing variables, including vessel geometry, impact energy, internal pressurization level, and impact location.
- The effect of impact locations was most discernable for the cylindrical COPVs. For the small cylindrical COPVs, the impact in the center of the hoop region was more severe than the impact near the transition zone. However, for the large cylindrical COPVs, the impact in the dome showed more damage than the impact in the hoop region.
- The statistical spread in BAI was relatively large. This made it difficult to determine distinct variable effects or to predict with any degree of confidence the residual burst pressure based on visual or NDI of the impact-damaged region.

C.5 References

C-1. C. A. Hare, Test Report, Enhanced Technology for Composite Overwrapped Pressure Vessels Program, Task 3.3, Graphite/Epoxy COPV Impact Damage Testing Database Extension, TR-936-001, NASA White Sands Test Facility, Las Cruces, New Mexico, September 1998.

C-2. J. B. Chang, *Enhanced Technology for Composite Overwrapped Pressure Vessels, Technical Summary Final Report*, TR-99(8504)-1, The Aerospace Corporation, February 2000.

Appendix D
NDE Techniques for Assessing COPV Impact Damage

D.1 Summary of NDE Techniques

Six NDE methods suitable for assessing impact damage to COPVs are discussed below. They are visual inspection, ultrasonic inspection, shearography, thermography, eddy current, and acoustic emission. Details about these techniques are discussed the following sections.

D.2 Visual Inspection

The easiest method for inspecting COPVs for mechanical damage is to perform a visual inspection. The outside of the COPV can be examined for signs of fiber damage using the unaided eyes. However, there is no quantitative reliability and confidence level associated with visual inspection capability. The impact energy level producing a damage state that cannot be detected by visual inspection is often called visual damage threshold (VDT).

The capability for visual inspection can be enhanced using magnification loupes. Also, the use of dye penetrant or alcohol wipes can sometimes accentuate indications. With a borescope, the inside liner of the COPV can be visually inspected for dents caused by impact. All these visual inspection techniques are hampered by any circumstances that limit visual access to the surface in question and by the poor surface contrast that typifies graphite/epoxy COPVs.

D.3 Ultrasonic Inspection

Ultrasonic inspection has been used in the aerospace industry for many years for detecting delamination or debonding of composite structures. Two ultrasonic techniques that can be used for detecting mechanical damage, including impact, are through-transmission and pulse-echo. With the through-transmission technique, a sound pulse generated by one transducer is received by a second after passing completely through the pressure vessel. With the pulse-echo technique, a reflection rod is inserted into the center of the vessel. Figure D-1 shows a C-scan representation of a COPV after a 7.4 ft-lb impact. The impact left no visible indication on the surface of the COPV; the impact site can be clearly identified by the dark region in the scan.

D.4 Shearography

Electronic shearography is a noncontact interferometric method for measuring changes in the out-of-plane slope of a surface. The application of shearography to COPVs requires an initial image of the vessel to be acquired and stored in the digital memory of a computer. After storing the initial image, a small load is applied to the vessel. Best results can be achieved by pressurizing the vessel to some small amount of pressure. A second image of the loaded or slightly deformed vessel is acquired and subtracted from the initial image. The result is a family of high-contrast fringes indicative of the deformation due to the pressure differential. Mechanical damage, such as impact to vessels, can cause subtle changes in load-carrying characteristics and, hence, the contours of the vessel that are effectively detected using shearography.

The shearography inspection technique is particularly effective in detecting impact in spherical COPVs because of the relatively uniform stress field, as shown in Figures D-2a and D-2b. The fringes presented in Figure D-2a represent the nominal deformation of a spherical COPV under 40-psi pressure. These fringes can be contrasted with the fringes in Figure D-2b that clearly indicate the location of a 15 ft-lb impact from a 1 in. tup.

A drawback to the use of the shearography in this application is the need for a matted surface to scatter the laser, creating the necessary speckle pattern. During testing, the vessels might have to be prepared using either a strippable paint or a spray powder. However, this approach should be evaluated for specific space applications.

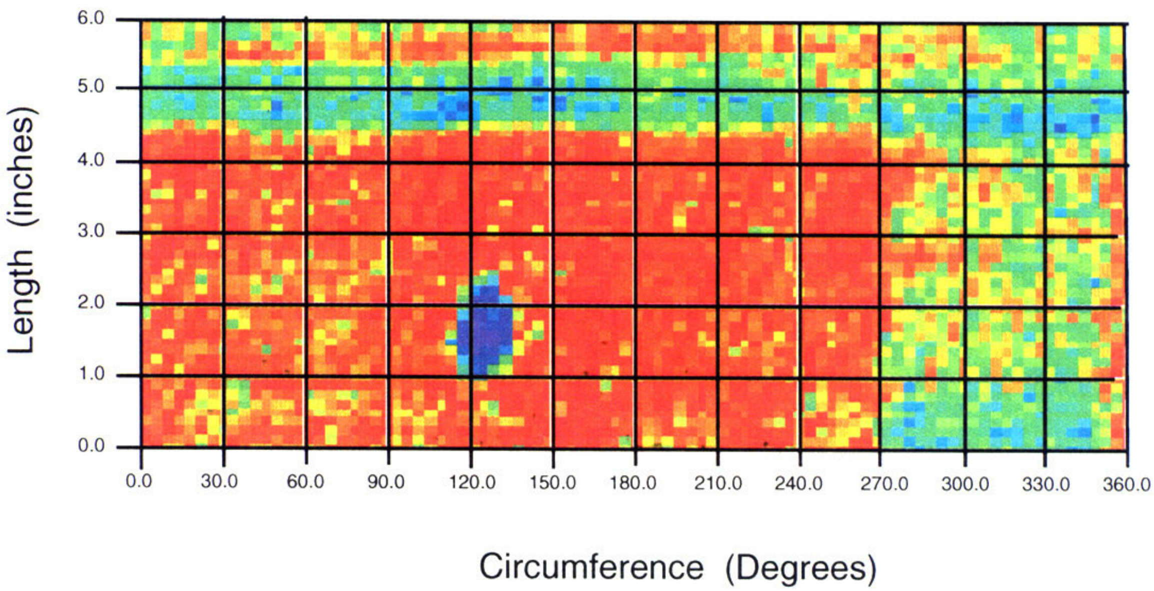
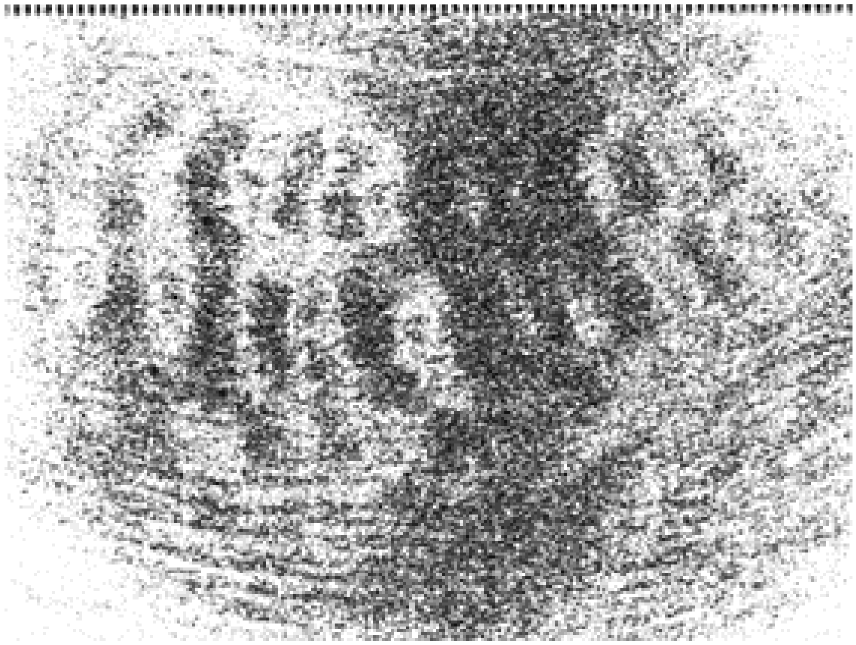


Figure D-1. Pulse-echo C-scan of a COPV subjected to a 7.5 ft-lb. impact.

D.5 Thermography

Thermography is an NDE technique for measuring the surface temperature of an object based on the emission of infrared (IR) radiation. Using an IR camera, the complete temperature profile of a target can be recorded at video frame rates (30 Hz). Variation in the surface temperature profile can occur as the result of internal discontinuity of flaws within the hardware. Flaws that produce localized variation in the thermal properties of a composite, such as delamination or porosity, can often be easily detected via thermography.

For a COPV, one possible consequence of an impact event is the creation of a disbond between the liner and overwrap of the impact site. In the damage area, significantly high thermal impedance can be formed. An increase of thermal impedance translates to higher surface temperature when the COPV is exposed to a transient heat source. The location of surface hot spots can then be mapped using an IR camera. Evaluation of IR data showed a bruised area to be as much as 4°F hotter than surrounding areas shortly after transient heating with a quartz lamp. Images obtained during the thermography inspection of a cylindrical COPV with both 11 ft-lb (13 J) and 25 ft-lb (20 J) impact sites are shown in Figure D-3.



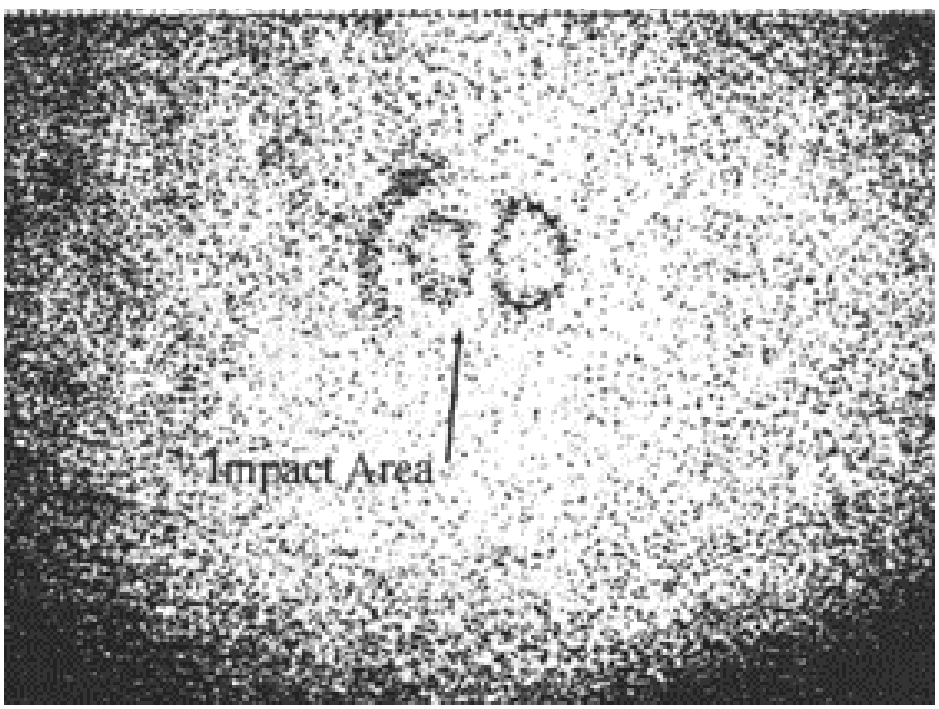


Figure D-2. (a) Initial shearography image. (b) Post-impact shearography image.

D.6 Eddy Current

Eddy current inspection is a commonly used NDE technique for detecting cracks in metallic parts of hardware. While the graphic fibers are conductive, the Gr/Ep COPVs are essentially transparent to the eddy current probes at standard inspection frequencies (less than 1 MHz). Within the COPV composite overwrap and metal liner, the overwrap acts as a spacer between the probe and the metal liner. Eddy currents that are very sensitive to the gap between the probe and the liner can be used to detect impact-induced dents in the liner. A simple eddy current image is shown in Figure D-4.

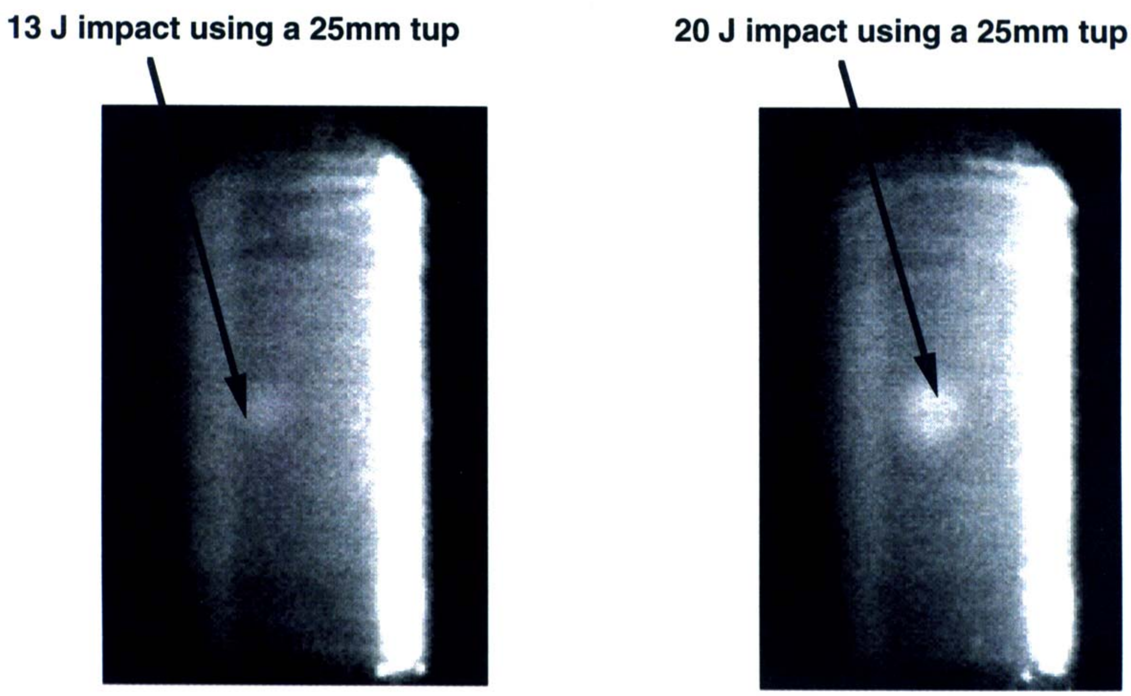


Figure D-3. Thermography indications on a COPV subjected to two impact levels.

D.7 Acoustic Emission

Loaded structures typically produce sound as the materials and components within the structure respond to the load. For composite hardware, matrix cracking or fiber breaking produces this sound. Acoustic emission (AE) monitoring is a method for evaluating the structural integrity of a structure based on the generation of sound during loading of the structure.

To detect impact damage that occurred in a COPV, the COPV can be subjected to an initial AE screening and then pressurized again after being subjected to an impact. Changes in the acoustic activity are noted, with the COPV exhibiting significantly more AE after impact above a given threshold. The energy threshold required for AE monitoring to detect impact varies significantly between COPV types. Figure D-5 demonstrates change activity that occurred after a 25 ft-lb impact on a cylindrical COPV.

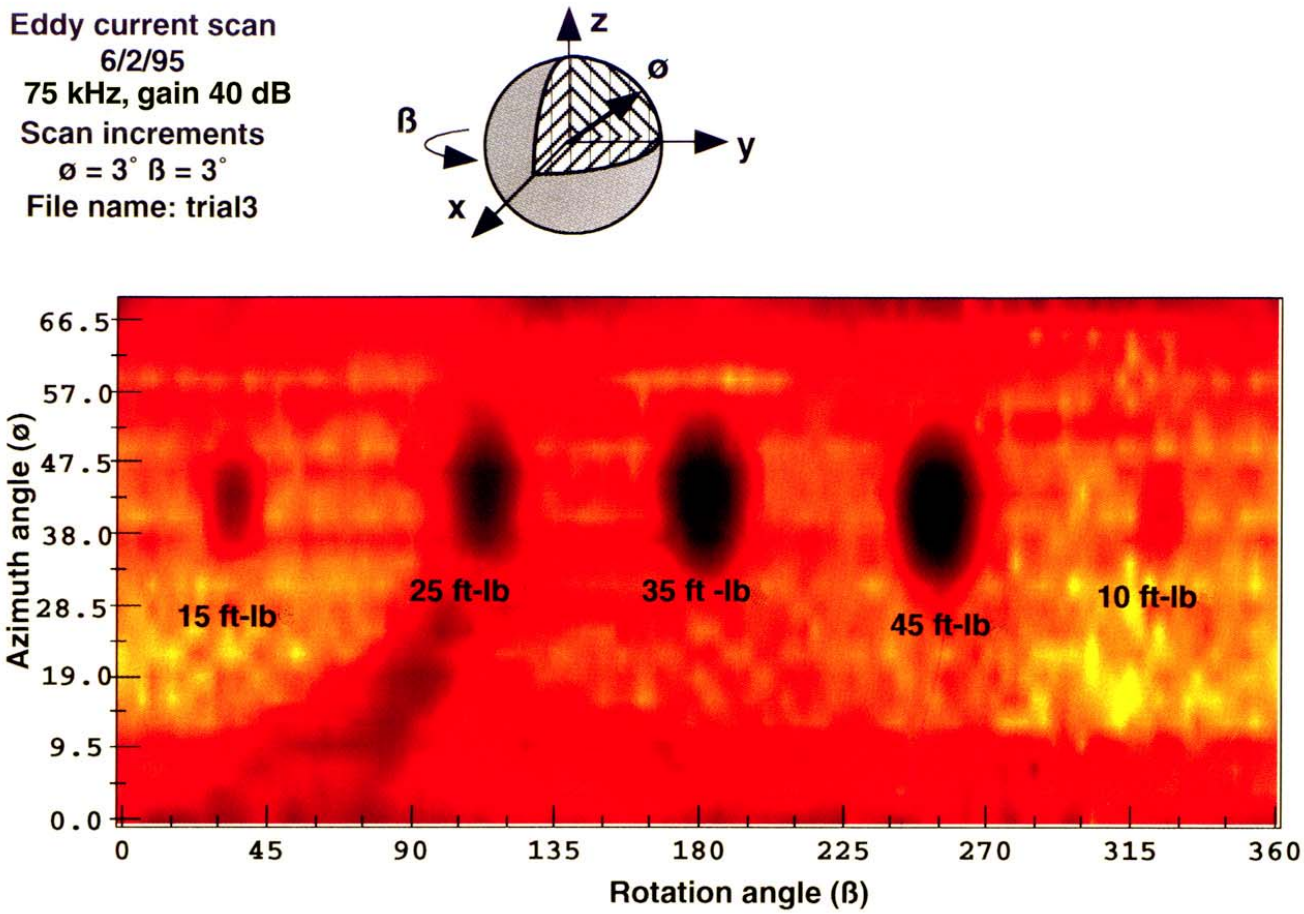


Figure D-4. Eddy current image of a COPV subjected to various impact levels.

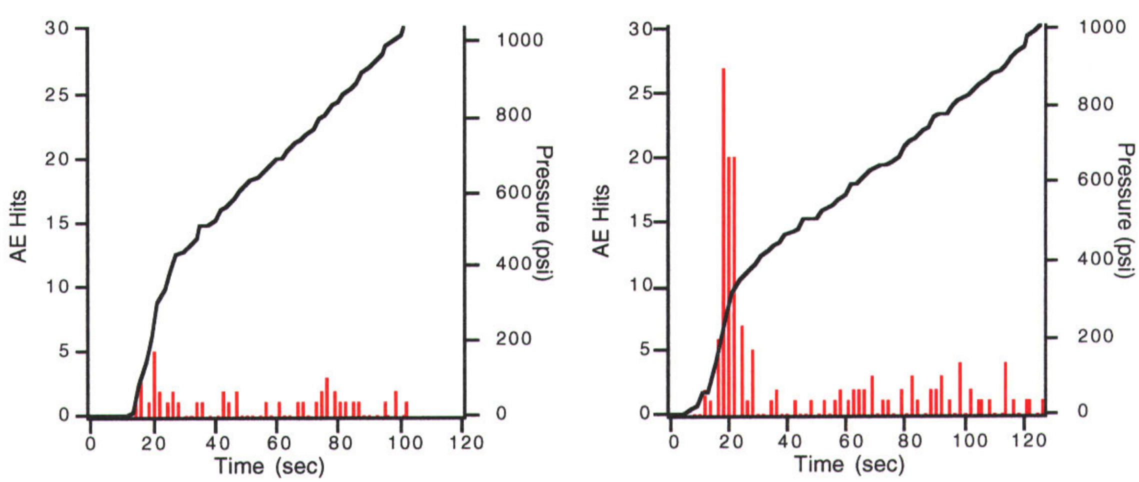


Figure D-5. Acoustic emission data: (a) Before impact and (b) After impact.

D.8 NDE Summary

A number of NDE techniques have been shown to be effective for detecting impact damage sites of Gr/Ep COPVs even if the impact energy is below VDT. Selection of the most appropriate technique(s) depends on a number of factors including:

- Specific type (size, shape, material thickness, coatings, etc.) of COPV to be inspected
- Accessibility constraints during inspection
- Required sensitivity

A guide for selecting an appropriate technique is presented in Figure D-6, drawn from Ref. D-1. In the figure, "whole field" refers to how the data are taken: point-by-point as in a scan versus whole field as in an acquired image. "Flaw characterization" is an assessment of how well the flaw is sized. "COPV preparation" refers to what must be done to the COPV to enable it to be inspected (coating the surface, etc.). "Field use" refers to how amenable the technique is to deployment in the field.

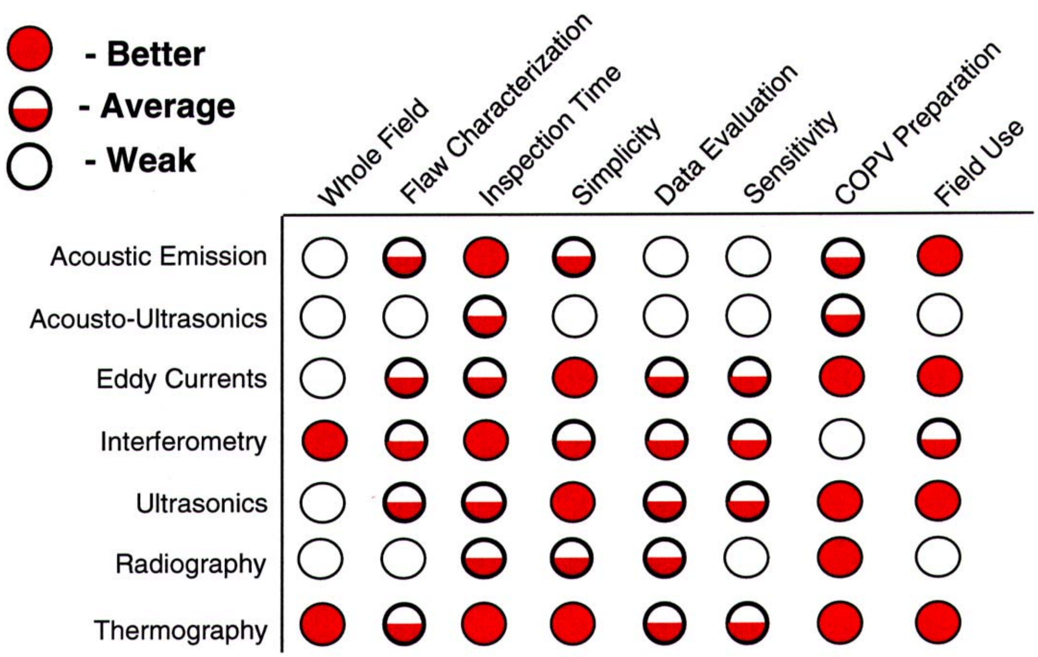


Figure D-6. Features of various NDE techniques for inspection of Gr/Ep COPVs.

D.9 Reference

D-1. E. C. Johnson and J. P. Nokes, *Nondestructive Evaluation (NDE) Techniques Assessment for Graphite/Epoxy (Gr/Ep) Composite Overwrapped Pressure Vessels*, TR-98(8504)-3, The Aerospace Corporation, October 1998.

Appendix E
Example of Proposed Impact Damage Control Procedures

A set of impact damage control (IDC) procedures for COPVs has been proposed by NASA-JSC WSTF under an Air Force/NASA–funded Research and Development Program (Ref. E-1). It is presented here as an example. The specific areas covered in this set of proposed procedures are: IDC plan; manufacturing IDCs; shipping IDC; COPV receiving inspection requirements; installation and system-level impact control; ICP implemented with impact indicators; and impact control plan (ICP) implemented with impact protectors.

E.1 Impact Damage Control (IDC) Plan

The first step in the preparation of an IDC procedure is to develop an IDC plan. The following sections provide a detailed approach for preparing an IDC plan.

E.1.1 QA and NDE

A quality assurance (QA) program, based on a comprehensive study and engineering requirements (e.g., drawings, material specifications, process specifications, workmanship standards, design review records, and fail mode analysis) for the COPV, should be established to assure that the necessary NDE and acceptance tests are effectively performed to verify that the flight article meets the requirements of the IDC Plan. The QA program should ensure that the COPVs conform to applicable drawings and process specifications; that no damage or degradation has occurred during material processing, fabrication, inspection, shipping, storage, operational use, and refurbishment; and that defects that could cause failure are detected or evaluated and corrected. Figure E-1 shows how QA and NDE efforts relate to BAI of COPVs. At a minimum, the following considerations should be included in structuring the QA program.

E.1.2 Inspection Plan

An inspection plan should be established prior to the start of fabrication. The plan should specify appropriate inspection points and inspection techniques for use throughout the program, beginning with material procurement and continuing throughout fabrication, assembly, acceptance proof test, operation, and refurbishment, as appropriate. In establishing inspection points and inspection techniques, consideration should be given to the material characteristics, fabrication processes, design concepts, structural configuration, and accessibility for inspection of flaws.

E.1.3 Personnel Qualifications, Training, and Certifications

QA and NDE inspectors should be trained and certified in the visual recognition of impact damage to a COPV. For visual inspections, the inspectors should be trained to identify impact damage indentations, cuts, matrix cracking, delaminations, and fiber breakage on representative COPV surfaces prior to performing the required COPV inspection. In addition, the inspectors should also be trained to differentiate benign discontinuities (e.g., scuff marks, adhesive films, and superficial abrasions) from the detrimental defects listed above.

Personnel involved in specialized NDI should be trained in the application of the technique and data interpretation. Specialized training should be conducted using representative impact damage on COPVs. All personnel handling the COPV should familiar with handling procedures associated with spaceflight hardware. At a minimum, this should include training in the damage susceptibility of the COPV and methods of preventing potential impacts during handling.

Discrepancy reporting should be defined as part of the QA program and inspection plan procedures. Discrepancies in terms of impact damage, indications, overwrap or liner discontinuities, anomalies, or other flaws should be reported and dispositioned on approved forms. Jurisdictional authority should give approval prior to pressurizing the COPV to MEOP levels or above.

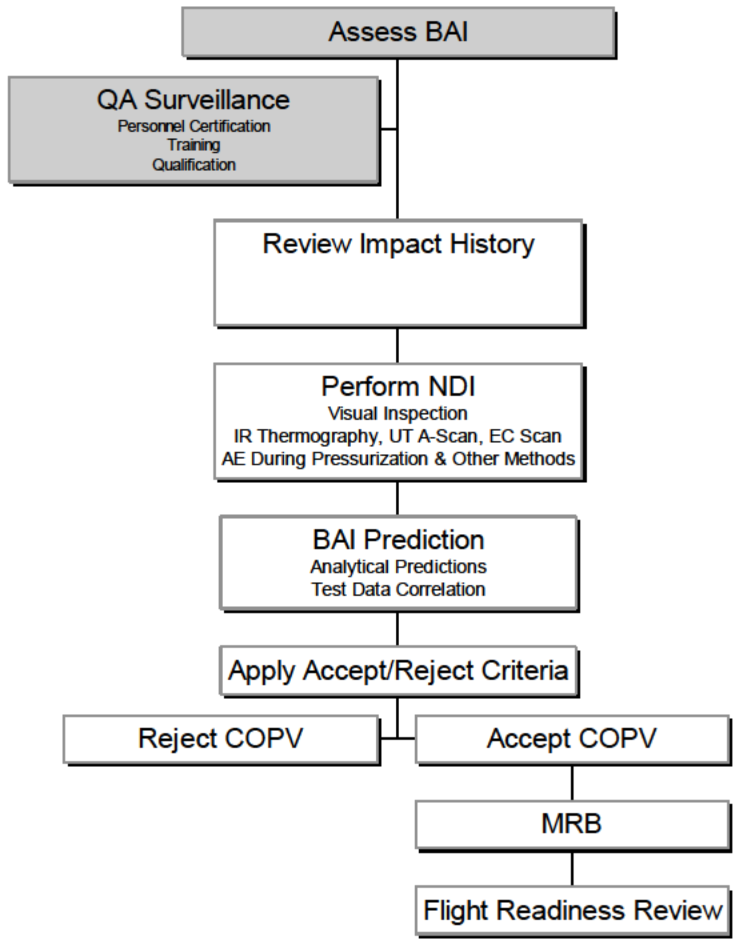


Figure E-1. Relationship of QA and NDE to BAI of COPVs.

E.2 Manufacturing Impact Damage Controls

Figure E-2 illustrates how the IDC Plan should be implemented during the manufacturing stage of the COPV. Handling procedures for manufacturing plant operations depend on the size of the COPV. For small cylindrical or spherical COPVs, manual handling should be accomplished with 100 percent QA surveillance using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required to move the COPV. Prevention of COPV impact damage should be controlled procedurally with 100 percent QA surveillance when using lifts and slings.

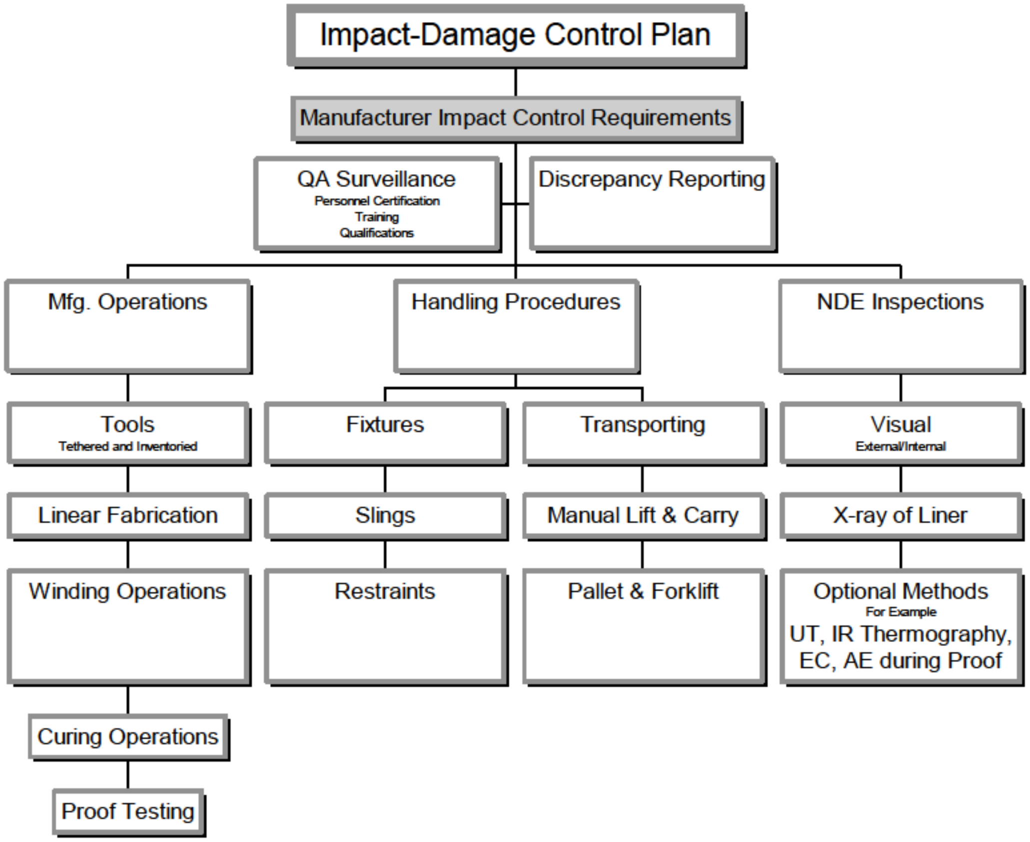


Figure E-2. Manufacturer's impact control requirements.

E.2.1 Impact Control for Manufacturing Operations

Impact control (IC) for manufacturing operations should include the identification of tool impacts, floor drop conditions, and threat environments that could potentially contribute to or cause COPV impact damage. Since impact protective covers may not be practical for all stages of COPV manufacturing operations, the plan requires that the IDC be implemented via procedural controls with 100 percent QA surveillance.

Tools in the IDC area of manufacturing plants should be inventoried and controlled by the QA program. Tethered tools on lanyards should be required for any situation that potentially may result in accidental dropping of tools that may strike the COPV during the manufacturing process. These processes include but should not be limited to filament winding, curing, autofrettage, leak testing, NDI, proof testing, and preparation for shipping or storage.

E.2.2 Impact Control for Manufacturer's Handling Operations

Impact control should include handling procedures for protective covers or fixtures used during all stages of manufacturing. The handling procedures should identify the certification requirements for lifting items such as slings, restraints, foam-padded chocks, fixtures, forklifts, or hoist assemblies.

Manual handling of COPVs in manufacturing plants should be performed with surveillance QA inspectors monitoring for any floor drops or transportation collisions. Likewise, COPV transportation requiring forklift or hoist mechanical aids should be performed using a trained team of personnel to guide the COPV and avoid collision impacts with objects, walls, or floors.

Protective measures, including impact protection covers, foam pads, foam-padded chocks, and foam-lined transportation containers, should be used to reduce the likelihood of anomalies or discontinuities (e.g., scuff marks or light abrasions) associated with various handling operations.

E.3 Impact Damage Control During Shipping

Figure E-3 illustrates the IDC Plan that should be implemented for COPV shipping. Handling procedures for shipping and receiving depend on the size of the COPV. For small cylindrical or spherical COPVs, handling should be performed under 100 percent surveillance using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required for moving the COPV. Prevention of COPV impact damage should be controlled procedurally when using lifts and slings.

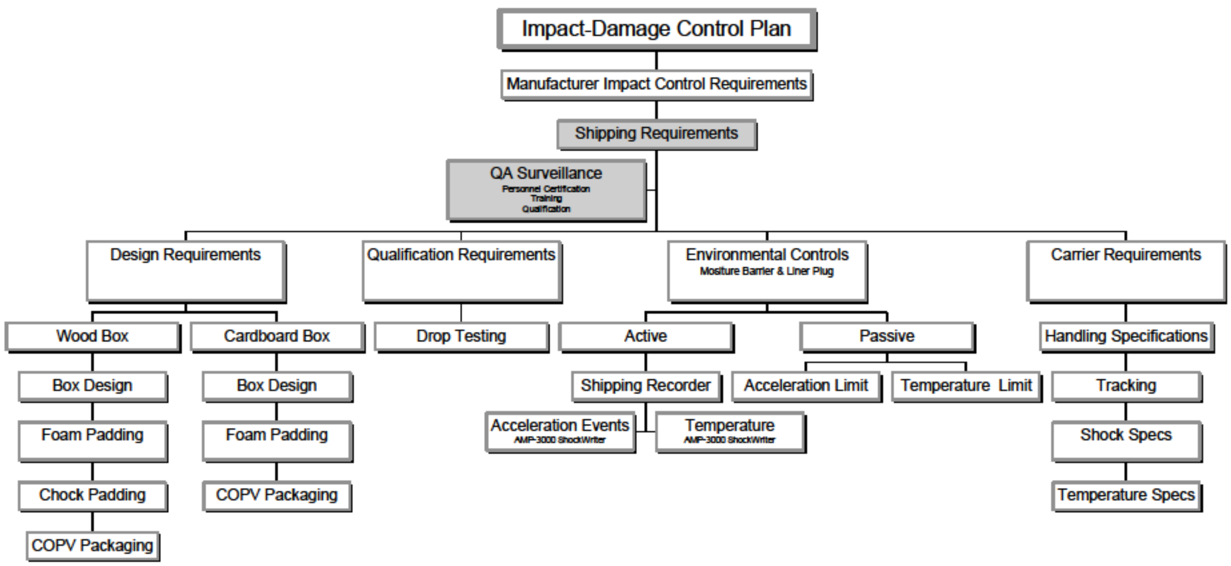


Figure E-3. Shipping ICP requirements.

E.3.1 Shipping Container Design

Transportation containers should be designed to protect the COPV from the threat environments encountered during shipping to assure that damage is not afflicted to the COPV. For small spherical COPVs, the shipping container should be foam lined per MIL-PRF-26514, “Polyurethane Foam, Rigid or Flexible, for Packaging.” Sufficient foam thickness is required to prevent COPV damage resulting from shipping container drops or collision impacts to the shipping container structure. The shock case defined by FED-STD-101C(4), Method 5007.1, Level B should be used to design the shipping container.

[Note: FED-STD-101C(4), “Test Procedures for Packaging Materials,” has been cancelled and superseded by MIL-STD-3010, “Test Procedures for Packaging Materials.” Appendix A in MIL-STD-3010 states that Method 5007 has been superseded by American Society for Testing and Materials (ASTM) D4169-04, “Standard Practice for Performance Testing of Shipping Containers and Systems.” The shock test procedure in cancelled FED-STD-101C(4) is clear, detailed, and preferred. Although it has been cancelled, this document remains available on DOD’s Acquisition Streamlining and Standardization Information System (ASSIST) Web site

< http://assist.daps.dla.mil/online/start/ > at no charge].

Frequently, larger or cylindrical COPV containers are suspended on foam chocks or foam-lined saddle fixtures. ASTM D1974–98(2003), "Standard Practice for Methods of Closing, Sealing, and Reinforcing Fiberboard Boxes," provides standard practices for closing, sealing, and reinforcing fiberboard shipping containers of types suitable for COPVs.

Shipping containers with multiple compartments should be permitted for the shipment of a plurality of small COPVs, but each compartment should be individually lined with sufficient foam to preclude impact damage during shipment. The entire crate should be designed to survive a drop from a height consistent with the threat environment (minimum 4 ft.) without inflicting damage to the COPV.

For large COPVs, shipping containers should be constructed to survive a minimum (4 ft.) drop while protecting the COPV. This includes suspending the COPV in foam pads, chocks, or saddles. The lid of the shipping container should be secured with metal clamps held in place with banding straps. The thickness of foam required to preclude COPV damage depends on the size and weight of the COPV. Small vessels may require only l-in.-thick foam, while the large vessels require foam pads up to 6 in. thick or greater. The foam lining specification should be in accordance with MIL-PRF-26514. ASTM D1083-91(1998), "Standard Test Methods for Mechanical Handling of Unitized Loads and Large Shipping Cases and Crates," provides appropriate test procedures, although it was withdrawn in 2001 and not replaced.

E.3.2 Shipping Container Qualification Testing

If the shipping container cannot be qualified by similarity to a previously qualified design, the new container design should be subjected to drop testing from a height consistent with the threat environment (minimum 4 ft.), with the COPV installed. The results of these drop tests should demonstrate that the BAI of the COPV does not degrade to below its design burst strength. ASTM D775-80(1986), "Method for Drop Test for Loaded Boxes," provides standard guidelines for drop testing loaded boxes, while ASTM D4169-04 (Section E.3.1 above) provides standard guidelines for performance testing of shipping containers and systems. [Note: ASTM D775-80 was withdrawn in 1993 and replaced by ASTM D5276-98(2004), "Standard Test Method for Drop Test of Loaded Containers by Free Fall."]

E.3.3 Shipping Container and Environmental Controls

The shipping container should be designed to protect the COPV from environmental factors that may degrade the performance of the COPV. The COPV should be sealed in a moisture barrier with an independent port boss seal that protects both the COPV overwrap and the liner from environmental exposure to high-humidity environments or from corrosive airborne contaminants during shipping and handling. Desiccants should be permitted, provided the chemical materials are compatible with the COPV overwrap and liner. ASTM D895-94, "Standard Test Method for Water Vapor Permeability of Packages," provides appropriate test procedures, although it was withdrawn in 1999 and has not been replaced.

The shipping container may also be equipped with active or passive acceleration and temperature recording devices to monitor the environmental shock conditions and temperature conditions during shipment. *In situ* health monitoring of shipping containers can be implemented with both passive and active devices. Passive monitors include shock-sensitive indicators that unload a configuration of spring-loaded balls or shock-sensitive strips that change color when the indicator has been subjected to a shock event. Active monitors include units such as the AMP-3000 ShockWriter, which is capable of storing up to several hundred events logged over a shipping duration of up to 90 days.

E.3.4 COPV Shipping Carrier Requirements

The shipping carrier should be qualified to ship and handle flight hardware. The shipping and handling documents should specify the acceptable ranges and limits with respect to shock, impact sensitivity, and temperature. The COPV cargo should be tracked throughout all stages of the shipping process.

E.4 COPV Receiving Inspection Requirements

Figure E-4 illustrates the ICP that should be implemented with respect to COPV receiving inspection requirements. Handling procedures for receiving inspection depend on the size of the COPV. For small cylindrical or spherical COPVs, manual handling should be accomplished with 100 percent QA surveillance using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required to move the COPV. Prevention of COPV impact damage should be controlled procedurally with 100 percent QA surveillance when using lifts and slings.

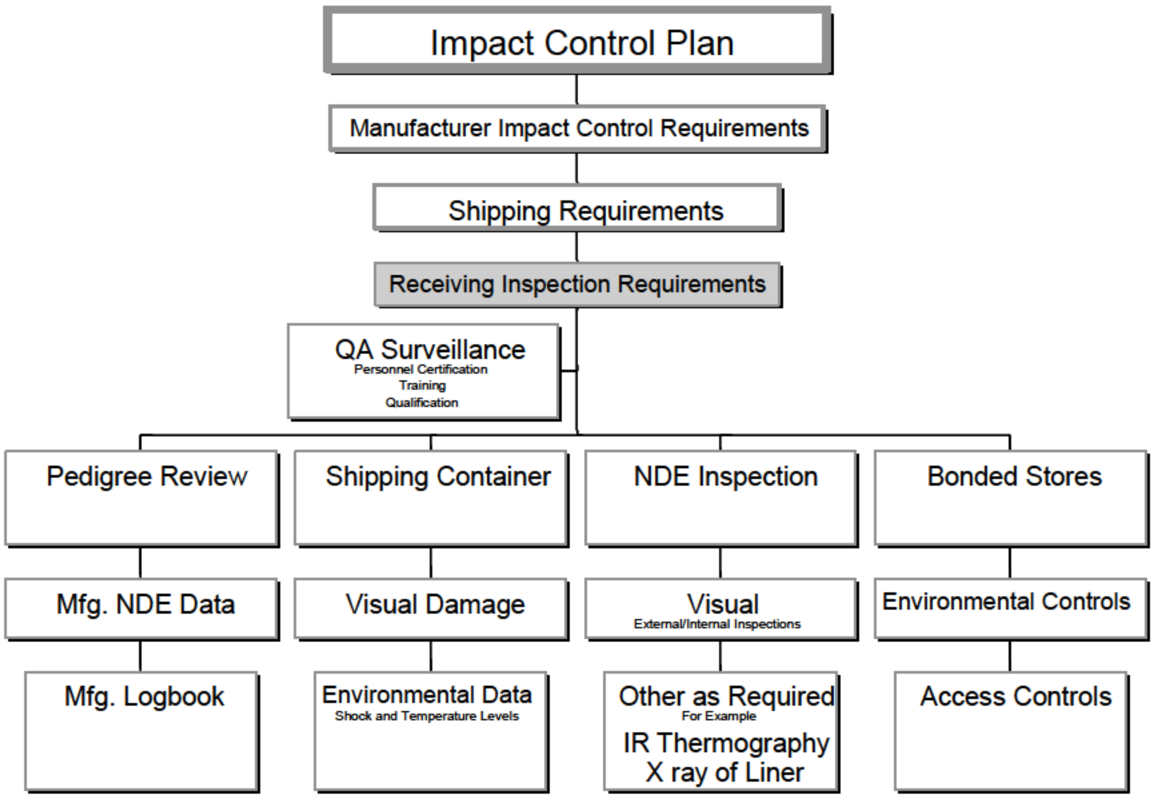


Figure E-4. Receiving inspection ICP requirements.

COPV receiving inspections should be performed to assess the integrity of the COPV as received. These inspections should include a visual inspection of the composite overwrap, a visual inspection of the COPV liner using a borescope, and an X-ray radiographic inspection of the metal liner.

E.4.1 Review of Pedigree Information

Pedigree information, shipped with the COPV, should be reviewed as part of the receiving inspection process to ensure that the COPV meets the program requirements. The manufacturer's NDE data should be reviewed and compared to procurement agency requirements for the COPV and the receiving inspection NDE records. The manufacturer's COPV logbook should be reviewed to determine if any suspected impact damage conditions have been reported.

E.4.2 Shipping Container Inspections

Visual inspection of the shipping container should be performed to determine if there are indications of a drop during shipment. Shipping container damage indications include crushed corners or impact indentations on the external surface. Internally, unusual foam deformation or compaction will provide clues of potential damage from shipping container drops.

If the shipping container is equipped with active or passive shock and/or temperature monitors, data from these units should be used to assess the environmental conditions during shipment of the COPV.

E.4.3 Bonded Stores

All COPVs not installed on spacecraft or launch vehicle hardware should be stored in a Bonded Stores facility with access controls defined by the program QA requirements. The Bonded Stores facilities should have environmental controls to maintain the COPV within the required temperature and humidity specifications.

E.5 Installation and System-Level Impact Control

Figure E-5 illustrates the ICP overview that should be implemented during the installation and system-level operations of the COPV mounted on the spacecraft hardware or the launch vehicle. COPV handling procedures for the spacecraft or launch vehicle installation and test phase depend on the size of the COPV. For small cylindrical or spherical COPVs, manual handling should be accomplished using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required to move the COPV. Prevention of COPV impact damage should be controlled procedurally with 100 percent QA surveillance when using lifts and slings.

E.5.1 ICP by Procedure Only

Figure E-5 illustrates the procedural-only ICP option that, if selected, should be used during the installation and test of the COPV mounted on the spacecraft hardware or the launch vehicle. Handling procedures for installation depend on the size of the COPV. For small COPV cylindrical or spherical vessels, manual handling should be accomplished using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required to move the COPV. Prevention of COPV impact damage should be controlled procedurally when using lifts and slings.

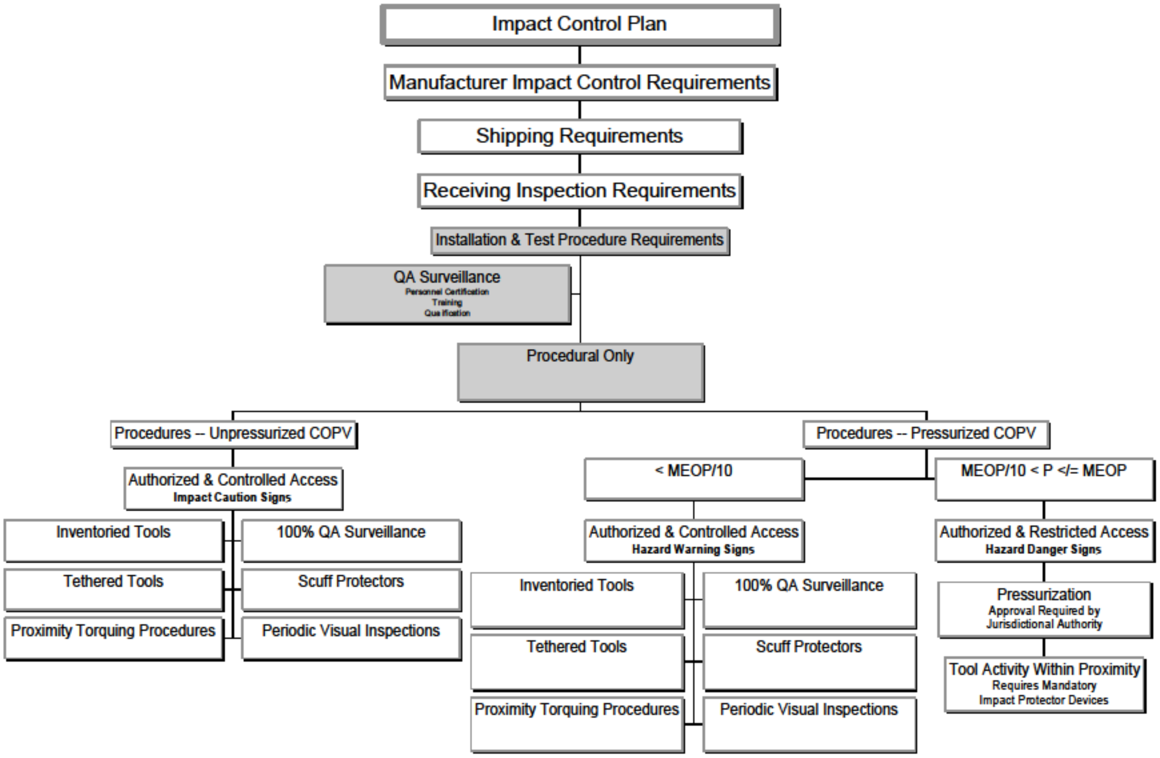


Figure E-5. Installation and system-level procedures for procedural-only ICP.

E.5.2 Procedures for Unpressurized COPVs

ICP procedures for unpressurized COPVs should require access control and authorization by the jurisdictional authority for personnel to work within close proximity to the COPV and should be performed with 100 percent QA surveillance. Caution signs should be displayed near the COPV to make personnel aware of the impact sensitivity. Inventoried and tethered tools should be required when this work is performed.

Torque or leverage tool operations within close proximity to the COPV should be performed under procedural control with 100 percent QA surveillance.

Scuff-protective materials in the form of high-density Ensolite®[1] foam or equivalent should be used to reduce the potential for false impact indications resulting from small tool scuffs and abrasions. Periodic inspections by trained and certified NDE inspectors should be performed prior to the installation of scuff-protective materials and after the removal thereof.

E.5.3 Procedures for Pressurized COPVs

Access control for working in close proximity to a pressurized COPV (< MEOP/10) should be controlled and authorized by the jurisdictional authority. Hazard warning signs should be displayed near the COPV to warn personnel of the impact sensitivity and the potential burst hazard of the COPV. ICP procedures for COPV pressurized to < MEOP/10 should require inventoried and tethered tools.

Torque or leverage tool operations within close proximity of the COPV should be performed under procedural control with 100 percent QA surveillance.

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[1] Ensolite® is a registered trademark of Ensolite.

Scuff-protective materials in the form of high-density Ensolite foam or equivalent should be used to reduce the potential for false-positive impact indications resulting from small tool scuffs and abrasions. Periodic inspections by trained and certified NDE inspectors should be performed prior to the installation of scuff-protective materials and after the removal thereof.

Pressurization of a COPV from 0.1 × MEOP to MEOP or above should require authorization by the jurisdictional authority, and personnel access should be restricted. Hazard danger signs should be displayed near the COPV to warn personnel of impact sensitivity and the potential for catastrophic burst. In addition, any tool activity performed within proximity of the pressurized COPV should require mandatory use of impact protector devices.

E.6 ICP Implemented with Impact Indicators

Figure E-6 illustrates the impact indicator ICP option that, if selected, should be implemented during the installation and test of the COPV mounted on the spacecraft hardware or the launch vehicle. Handling procedures for installation depend on the size of the COPV. For small cylindrical or spherical COPVs, manual handling should be accomplished using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required to move the COPV. Prevention of COPV impact damage should be controlled procedurally when using lifts and slings.

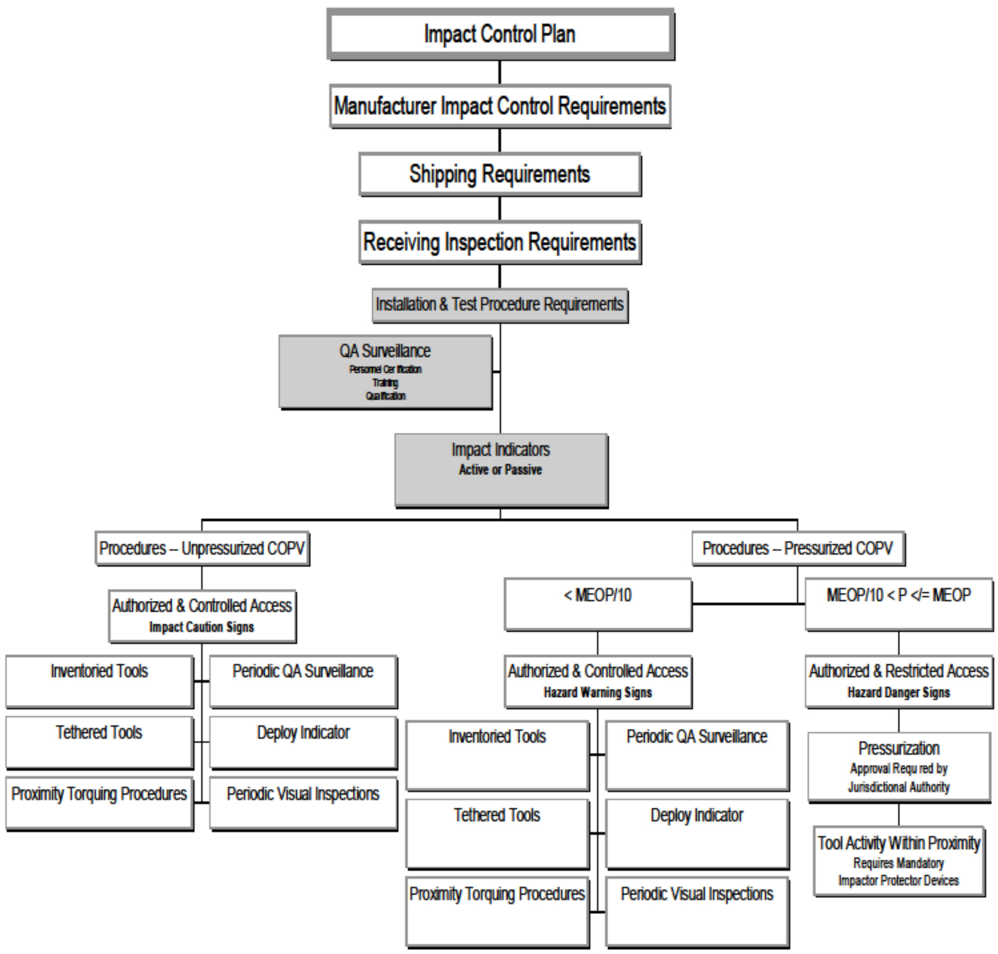

Figure E-6. Installation and system-level procedure for implementation of ICP with impact indicators.

E.6.1 Design Requirements for Impact Indicators

Impact indicators should be capable of detecting any impact condition that could result in a 5 percent or greater degradation of COPV nominal burst strength. Piezoresistive film, commonly used as strain and force sensors, sandwiched between two 0.25-in.-thick high-density Ensolite foam layers provides an excellent active impact indicator with impact force discrimination. By using an electrical comparator circuit on the active indicator, a threshold can be set to respond only to detrimental impacts and ignore all low-energy events.

Other types of passive indicators include bubble dye wraps, pressure-sensitive films, deformable covers (e.g., metal honeycomb and polystyrene foam), and thin plexiglass or glass covers. The passive indicators should have the means for discriminating detrimental impacts from low-energy events (tapping, touching, scuffing) that will not compromise the burst strength of the COPV.

E.6.2 Procedures for Unpressurized COPVs

ICP procedures for unpressurized COPVs using impact indicators should require access control and authorization by the jurisdictional authority to work within close proximity to the COPV. Caution signs should be displayed near the COPV to make personnel aware of the impact sensitivity. Inventoried and tethered tools should be required when this work is performed as a prudent means of avoiding impact situations that require disposition. Periodic QA surveillance should be performed to monitor the impact indicators.

Torque or leverage tool operations within close proximity to the COPV should be performed under procedural control with 100 percent QA surveillance.

Scuff-protective materials in the form of high-density Ensolite foam used with an impact indicator should be used to reduce the potential for false impact indications. Periodic inspections by trained and certified NDE inspectors should be performed prior to the installation of the impact indicator device and after the removal of such materials. Any impact indicator device should be installed with protective high-density Ensolite foam to preclude any scuff or abrasion marks that may have to be analyzed as suspected impact conditions.

Pressurization of a COPV from $0.1 \times$ MEOP to MEOP or above should require authorization by the jurisdictional authority and personnel access should be restricted. Hazard danger signs should be displayed near the COPV to warn personnel of impact sensitivity and the potential for catastrophic burst. In addition, any tool activity performed within proximity of the pressurized COPV should require mandatory use of impact protector devices.

E.7 ICP Implemented with Impact Protectors

Figure E-7 illustrates the impact protector ICP option that, if selected, should be implemented during the installation and system-level operations of the COPV mounted on the spacecraft hardware or the launch vehicle. Handling procedures for installation depend on the size of the COPV. For small cylindrical or spherical COPVs, manual handling should be accomplished using procedures that specify the use of gloves and foam pads to prevent scuffing of the composite overwrapped surface. For large COPVs, lifts and slings should be required to move the COPV. Prevention of COPV impact damage should be controlled procedurally when using lifts and slings.

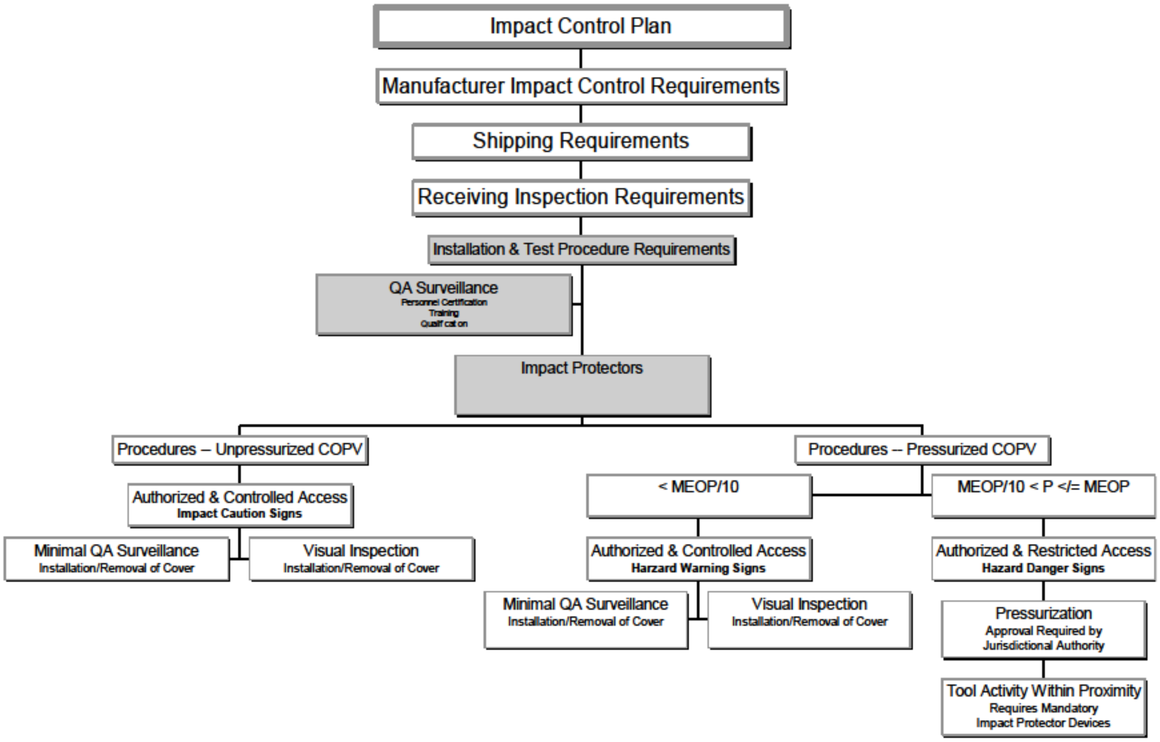

Figure E-7. Installation and system-level procedure for implementation of ICP with impact protectors.

E.7.1 Design Requirements for Impact Protectors

Impact protectors should be capable of shielding a COPV from impact damage consistent with the threat environment or at least up to the load limits for the integral boss and mounting fixtures. An impact inflicting any damage that potentially degrades the burst strength of the COPV more than 5 percent from its nominal burst pressure is unacceptable.

The minimum design cross-section of an impact protector cover should include the shielding layers depicted in Figure E-8. The indentation damage from a credible impact should be completely absorbed by a hard shell fabricated from fiberglass/epoxy, Kevlar®[2]/epoxy, or equivalent material sufficiently thick to absorb the indentation energy without penetration. The potential deflection damage should be mitigated by spreading the peak loading transmitted through the hard shell over an area consistent with the dimensions of the COPV. Deflection damage should be further mitigated by introducing an energy-absorbing material between the hard shell and the COPV. Aluminum mesh foam (20 pores/in., 0.5 in. thick), manufactured by ERG Materials, Inc., is an example of energy-absorbing material that has been qualified for this application. Other materials with equivalent energy-absorbing properties can be qualified for this application. Finally, if an impact indicator is used in combination with the impact protector, it should be bonded to a thin (1/16-in.-thick) layer of interface material (e.g., fiberglass/epoxy composite or polymeric materials). The laminated impact protective cover should be installed over a layer of high-density Ensolite foam mounted directly on the COPV.

[2] Kevlar® is a registered trademark of E. I. DuPont deNemours and Company.

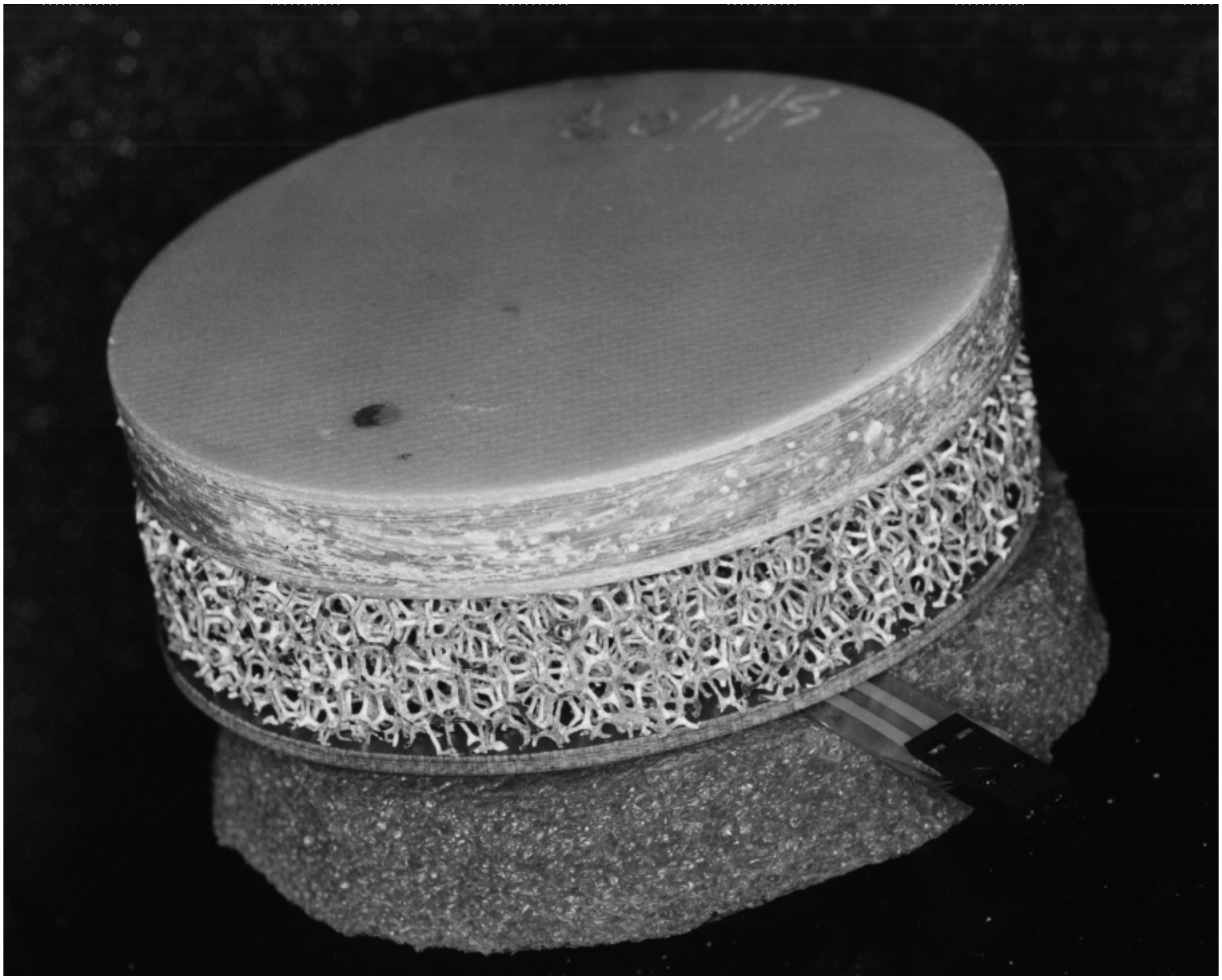

Figure E-8. Cross-section of COPV impact protector.

The impact protector device should be qualified by testing on a representative qualification COPV to provide adequate protection up to a specified or credible impact condition (e.g., 35 ft-lb impact with a 0.5 in. hemispherical tup or tool). The impact protector should then be labeled accordingly and controlled procedurally for impact protection within the specified limits. Periodic QA surveillance should be required to ensure that the impact protector is used in accordance with its specifications and that a damaged impact protector is not used for primary protection of a COPV. Any impact protector subjected to an impact that crushes or deforms the energy-absorbing material should be rejected for further use and discarded.

E.7.2 Procedures for Unpressurized COPVs

ICP procedures for unpressurized COPVs using impact protectors should require controlled access authorized by the jurisdictional authority to work within close proximity of the COPV. Caution signs should be displayed near the COPV to make personnel aware of the impact sensitivity and to utilize the impact protective covers.

Periodic QA surveillance should be performed to monitor that the impact protectors are being used.

Impact protector devices should be installed with scuff-protective high-density Ensolite foam to preclude any scuff or abrasion marks that may be mistakenly identified as a suspected impact discontinuity. Periodic inspections by trained and certified NDE inspectors should be performed prior to the installation of the impact protector device and after the removal of such materials.

E.7.3 Procedures for Pressurized COPVs

Access for working in close proximity to a COPV pressurized below MEOP should be controlled and authorized by the jurisdictional authority. Hazard warning signs should be displayed near the COPV to warn personnel of the impact sensitivity and the potential burst hazard of the COPV.

Scuff-protective materials in the form of high-density Ensolite foam (either used directly as part of the impact protector or as additional scuff-protection measures) should be used to reduce the potential for false impact indications. Periodic inspections by trained and certified NDE inspectors should be performed prior to installation of scuff-protective materials and after removal thereof.

Pressurization of a COPV from 0.1 × MEOP to MEOP or above should require authorization by the jurisdictional authority, and personnel access should be restricted. Hazard danger signs should be displayed near the COPV to warn personnel of impact sensitivity and the potential for catastrophic burst. In addition, any tool activity performed within proximity of the pressurized COPV should require mandatory use of impact protector devices.

E.8 Reference

E-1. R. M. Tapphorn, *Test Report, Impact Damage Effects and Control Applied to Composite Overwrapped Pressure Vessels*, TR-806-001, NASA Johnson Space Center, White Sands Test Facility, July 29, 1998.

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