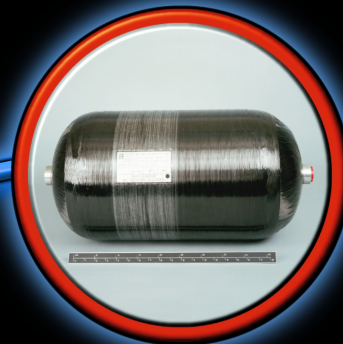
Inspection for Damage to Carbon/Epoxy Composite Overwrapped Pressure Vessels



NASA White Sands Test Facility

August 2010

Section	Change
Instructors	
Nathanael Greene	Updated Nate's information as requested
Introduction	
Course Materials	This is a new section added
Aerospace Requirements Commercial Requirements	Divided out *Background of Requirements* into these two sections
Document Status	Added *S-089*, *Pressurized Composite Structure* and *SMC Military Handbook (TOR)*
Terminology	Added *Critical Damage, Finite element analysis (FEA)*, and *Instrumented Mechanical Impact Tester*
COPV Manufacturing and Production	
Safe Handling	This is a new section added after *Health and Safety*
PV Classification	Added Type V bullet to list; removed *DOT Rating*
COPV Manufacturers	Replaced Carleton with Cobham and added Structural Composites Industries
Load Sharing of PVs	This section and table was added after *PV Classification*
Flight Weight COPVs	This is a new section added after *COPV Manufactures*
Commercial COPVs	This is a new section added after *Flight Weight COPVs*
Damage Mechanisms	
COPV Program Test Articles (Flight Qualified Design)	This is a new section added after *COPV Program Test Articles* images
Long Term Summary	This is a new section added after the *6 month Summary*
Stress Rupture Testing	This is a new section added after *Long Term Summary*
Following Stress Rupture Testing	Added 3 images of Stress Rupture Facility
Pad Abort (PA-1) COPV Testing	This is a new section added after *Impact Control Plan*
Impact Results	This is a new section added after *Pad Abort (PA-1) COPV Testing*
Burst Results	This is a new section added after *Impact Results*
Following *Burst Results*	Added Impact/Burst Photos
Materials COPV Testing	Added an image of NTO Coupon Damage Detail before *Materials COPV Testing*
After Small Sphere Table	Replaced image of SCI Subscale Vessel after N_2O_4 Exposure and added new image of COPV after pressurized NTO exposure
Future Work	This is a new section added after *Summary*
Progressive Failure Analysis	
Composite Materials	*Metallic liner* and *Tensile dominated structure* were added to the list
Summary	*Inner laminate deply* and *Liner Buckling* were added to the list
Quiz #	The quiz number was change from 4 to 5
Impact Control and Protection	
Industry Survey and Involvement	*Damage detection course (1999)* and *CPS Safety Summit Technical Interchange Meeting (late 2009)* were added to the list
Damage Indicators	*Note: 5 ft-lb correlated to impact data results* was added after the list
Impact Indicators	*Note: Must be able to manage false positives* was added after the list
Inspection Plan	*Note: Problematic for Composites* was added after the list
Inspection Techniques	*Currently applies to metallic regions* was added to the list
Precision Clean	This entire section was added in between *Impact Control and Damage* and *Receiving and Periodic Inspection*
Receiving and Periodic Inspection	
Periodic Inspection Schedule	Added *Prior to instrumentation application* and *Prior to integration* to

Section	Change
	the list
Inspections since COPV Program	This is a new section added after COPV Program Inspections
Written Procedures	Updated *Inspection Checklist Record*
Mechanical Damage Indications	
Fiber: Cuts, Breaks, Terminations	*Tow termination* was added to list
Scuffs and Abrasions	*Cross Fiber and Along Fiber* were added to the list under Directionality
	Material transfer was added to the list
Surface Inclusions	*Note: Generally are artifacts of the manufacturing process*
Lean or Rich Resin	Added *Burst bubbles can look like dents* and *Excess resin provides protection and weight* under Indicates poor process control
Visual Inspection Assisted by	The section was rewritten
Key VT Report Information	The section was updated and rewritten
	Replaced COPV Visual Inspection Report with *COPV Pre-Visual Inspection Checklist* and Blank forms
Damage Location	Added *Note clockwise verses counter-clockwise and orientation* to the list
Importance of Proper Recordkeeping	Changed title from *Importance of Good Identification*
	Added *Large components* and *Multiple Damage Sites* to the list
Inspection Techniques	
X-ray Radiography	*Needs more development and standardization* was added to the list
	Typical X-ray image added
What about X-ray	This section is new
Flash Thermography	Added two new images under this section
NDE Application Matrix	The matrix has been updated
Visual Inspection and Surface Photos	
Impact Condition Legend	Changed title from *Impact Condition Code*

Instructors

Nathanael Greene

Mr. Nathanael Greene is a Mechanical Engineer and Combustion Scientist at the NASA White Sands Test Facility (WSTF) in Las Cruces, New Mexico. He has worked in Fire Safety for the NASA Glenn Research Center and in Structures at the NASA Johnson Space Center. Nathanael is currently the NASA Project Manager at WSTF responsible for leadership of the composite pressure systems (CPS) core capability. He has experience in composite pressure vessels (CPV), composite structures, flammability, and hydrogen and is active the U.S. and international CPV community in test, evaluation and standards development.

Tommy Yoder

Tommy B. Yoder received a Bachelor of Science degree in Mechanical Engineering from New Mexico State University. He has over 15 years of Composite Overwrapped Pressure Vessel (COPV) experience at White Sands Test Facility (WSTF). COPV support testing at WSTF has been performed for numerous aerospace and commercial programs including Space Shuttle, International Space Station, Orion, and Constellation. Yoder was the test conductor for material compatibility, mechanical damage, and burst testing during the joint USAF/NASA COPV program. Currently, he is the COPV Group Leader and project leader for several COPV projects at WSTF. Additionally, he is a senior test conductor in WSTF's Hazardous Fluids and High Pressure Test Areas. Yoder is an active member of AIAA, ASTM, and CSA standards working groups dedicated to the safe application of COPV technology. He has inspected hundreds of COPVs ranging from various test experimental vessels to flight vessels from the Shuttle and AMS-02. Other related aerospace experience includes project leader for the Shuttle APU Tank Fleet Leader Program, ATLAS V solid rocket motor case, and Ascent Abort (AA-1) visual damage threshold test program.

Syllabus

Objective: To train aerospace flight hardware visual inspectors detect visible damage to the composite shell of Graphite/Epoxy COPVs. This course satisfies requirements of KHB 8715.3 (latest revision), AIAA S-081, AIAA S-081A, and AFSPCMAN 91-710 for trained visual inspectors of flight-weight COPVs.

Instructors: Nathanael Greene, and Tommy Yoder

Day 1

0800 Introduction and Orientation
Welcome to Damage Detection Course
Introductions of presenters and attendees
Course overview and objectives

Terminology and Acronyms
Definitions

Break

COPV Manufacturing
Fiber production
COPV manufacturing

Damage Mechanisms
Baseline burst testing of undamaged COPVs
Failure mode/safe life testing of undamaged COPVs
Impact damage effects
Effects of pressurized storage and impact
Impact damage summary
Incompatible fluids exposure testing

Lunch

Site Tour and NDE Demonstration

Damage Progression
Composite damage phenomena
Thermal deply analysis technique
Thermal deply results

Break

Inspection Techniques
COPV program NDE
NDE techniques
Correlation of techniques
Application of techniques

General Discussion
Review discussion topics

Day 2

0800 Review of Day 1
Damage mechanisms
Progressive failure analysis
Receiving and periodic inspection

Impact Control and Protection
Industry survey and findings
Impact control plan
Impact protectors and impact control requirements
Credible threat analysis
Impact control and protection summary

Receiving and Periodic Inspection
Visual inspection documentation
Visual inspection procedures

Review Visual Inspection and Surface Photos
Types of defects, origins, and importance
Manufacturing anomalies
Impact damage and variables

Break

Demonstration of Techniques
Demonstration of Acoustic Impendence Testing

Visual Inspection Demonstration
Discussion of pre-inspection readiness
Demonstration of visual inspection

Lunch

Group Visual Inspection of COPVs
COPV Visual Inspections
Review of findings
Discussion of Results and Dispositions

Break

Exit Activities
Exit exam
Course critiques
Certificates of course completion
Exit remarks and recommendations

Introduction

Course Objective

- Train visual inspectors of aerospace flight hardware to detect visible surface damage to composite overwrapped pressure vessels (COPV) per requirements:
  - KNPR 8715.3 (latest Rev)
  - ANSI/AIAA S-081 and S-081A
  - AFSPCMAN 91-710; Vol. 3 & 6 (July 2004)

What is a COPV?

- Pressure vessel constructed by overwrapping a liner with fiber/epoxy resin
  - Liner (Metal or Plastic)
  - Fiber (Kevlar, Carbon, Zylon, and Hybrids)
- Reduces weight, increases performance
- Used for system pressurization, propellants, and other fluid storage

Background of Requirements

- MIL-STD-1522A inadequate for composites
  - Mars Observer highlighted issue
- Interim policy letter
- KHB 8715.3 Rev. D
  - Currently KNPR 8715.3 Rev. F
- ANSI/AIAA S-081
- AFSPCMAN 91-710 (Vol. 3 & 6)

Interim Policy Letter

- Signed jointly by USAF, NASA Safety and Reliability, KSC Chief of Safety, and 30th and 45th Space Wing
- Issued as interim requirement while COPV program was developing data to be incorporated into replacement documentation
- Recognized unknowns regarding COPV design and damage tolerance

Policy Letter Requirements

- Design shall demonstrate safe life
- Before first pressurization at launch facility, vessel will be visually inspected
- Vessel must pass a 1.1X MEOP pressure test before use
- Nondestructive inspection as necessary

KHB 8715.3 Rev. D

- Incorporates interim policy letter requirements
- Includes inspection by a certified, trained inspector

Trained vs. Certified

- Policy letter and KHB 8715.3 Rev. D state the requirement for ASNT certification
- Reality – ASNT certification unavailable for composites

What Is the COPV Program?

- Joint program: NASA-Code Q, USAF-SMC, and 45th Space Wing
- Purpose: develop data related to all phases of COPV manufacturing and use. Apply the resulting program data to update 1522A.
- Original program duration of two years; actual completion time was five years
- Data generated for flight-qualified spherical and cylindrical designs being used as high pressure He tanks (Gr/Ep wrapped over metallic liners)
  - Materials selection
  - Manufacturing
  - Design
  - Damage tolerance
- WSTF responsible for damage tolerance testing and database

COPV Program Video

Document Status

- Industry standards (ANSI/AIAA)
  - S-080, Metallic Pressure Vessels, Pressurized Structures, and Pressure Components (1998)
  - S-081A, Composite Overwrapped Pressure Vessels (COPVs) (2006)
  - S-082, Composite Structures, in work
  - S-087, Composite Pressure Vessels, in work
- Government standards
  - KNPR 8715.3 Rev. G
  - AFSPCMAN 91-710; Vol. 3 &6 (July 2004)

What's Next?

- Revisions to KNPR 8715.3 Rev. G
- Revisions to AFSPCMAN 91-710 (Vol. 3 & 6)
- SMC has prepared Mil Handbook (TOR)
- S-081A, *Composite Overwrapped Pressure Vessels (COPVs)*
- ***All incorporate WSTF program data***
- ***All require an impact control plan (ICP)***

Quiz #1

Which document does not require trained visual inspectors:

A. ANSI/AIAA S-081A-2006
B. AFSPCMAN 91-710
C. Mil-STD-1020A
D. KNPR 8715.3 Rev. G

Terminology

Acceptance test **-** Required formal test on flight hardware to verify that materials, manufacturing processes, and workmanship meet specifications and that hardware is acceptable for intended use.

Authority having jurisdiction (AHJ) **-** Organization responsible for maintaining safety and mission assurance at manufacturing plant, contractor facility, or launch facility.

Autofrettage **-** Pressure cycle to which a metal-lined COPV is subjected with the intent of yielding the liner or a portion of the liner. (NOTE: this operation may be considered part of the manufacturing process)

Burst strength after impact (BAI) **-** The residual strength of the COPV after mechanical damage (impact) has occurred.

Burst factor (BF) **-** Multiplying factor applied to maximum design pressure to obtain design burst pressure.

Burst before leak (BBL) **-** COPV failure mode in which the vessel fails catastrophically under pressure before it leaks.

Burst upon impact (BUI) **-** Failure mode, usually catastrophic, caused by a mechanical impact of a pressurized COPV. Independent of leak before burst.

Critical impact energy (CIE) **-** The amount of mechanical impact energy that lowers the COPV strength or cycle life such that it no longer meets strength requirements.

Composite overwrapped pressure vessel (COPV) **-** A pressure vessel constructed by filament winding layers of epoxy coated fiber over a metallic liner.

Design burst pressure **-** Pressure that vessel, component, or pressurized structure must withstand in applicable operating environment without rupture.

Design safety factor (DF or FOS) **-** Factor used to account for uncertainties in material properties and analysis procedures; also called design factor of safety or simply, 'factor of safety'.

Finite element analysis (FEA) **-** A numerical technique for finding approximate solutions of partial differential equations

Flight readiness review (FRR) **-** Process conducted by the authority having jurisdiction to determine whether a system is ready for launch, including all operational and safety aspects.

Graphite and Epoxy (Gr/Ep) **-** Carbon fiber and resin system that makes up the composite overwrap of a COPV.

Impact damage **-** Induced fault in composite overwrap or metal liner caused by an object strike on the vessel or vessel strike on an object.

Impact damage threshold (IDT) **-** Maximum impact energy level that will not degrade residual strength of COPV below design burst. The impact energy is equal to (DF)x(VDT), where DF $\geq$ 1.25 (fixed).

Impact control plan (ICP) - Approved process addressing COPV damage prevention and protection from potential mechanical damage from cradle to grave.

Impact damage protection - Physical device that helps prevent mechanical damage from occurring (i.e. protective cover).

Instrumented mechanical impact tester (IMIT) -. A dead weight tested that is instrumented to collect load and velocity during a impact event.

Leak before burst (LBB) - COPV failure mode in which the vessel leaks under pressure before it bursts. Normally only applies to metallic liner.

Material review board (MRB) - Independent technical board assembled by AHJ to assess failure analysis results after damage is identified.

Maximum expected operating pressure (MEOP) - Highest pressure expected for pressure vessel, component, or pressurized structure to undergo during service life and still retain functionality in applicable use environments.

Nondestructive evaluation (NDE) - Term used to encompass all activities associated with nondestructive testing (NDT), nondestructive inspection (NDI), and nondestructive examination (NDEx).

Progressive failure analysis (PFA) -An analysis method using iterative progressive loading coupled to Finite Element Analysis (FEA) and Microstructure modeling allowing for incremental material degradation and redistribution of loads within a composite structure to model damage accumulation up to the point of failure.

Proof factor - Multiplying factor applied to MEOP to establish proof pressure.

Proof pressure - Product of MEOP, proof factor, and factor accounting for difference in material properties between test and service environment, such as temperature; proof pressure provides evidence of satisfactory workmanship and material quality and/or establishes maximum initial flaw sizes for safe-life demonstration.

Qualification tests - Required formal tests that demonstrate whether design, manufacture, and assembly have resulted in hardware designs conforming to specification requirements.

Residual strength - Maximum value of nominal load (stress) that a cracked body can sustain without unstable crack growth.

Residual stress - The stress remaining in a structure from processing, fabrication, assembly, testing, or operation.

Service life - Required time period or specified stress cycles a COPV undergoes, from manufacturing through acceptance testing, handling, storage, transportation, launch and orbital operations, refurbishment, retesting, orbital reentry or recovery, and reuse; "cradle to grave".

Ultrasonic inspection (UT) - NDE technique that uses sound wave reflection to locate a damage-affected delamination zone on a COPV.

Undetectable indication - Abnormality, defect, or damage that cannot reliably be detected by visual inspection (subsurface damage).

***Visual detection threshold (VDT)* -** Impact energy level that creates an indication barely detectable by trained inspector using unaided visual technique.

***Visual inspection (VI)* -** NDE technique that uses trained visual inspectors to evaluate COPV shell and liner for evidence of damage or non-conformance.

Quiz #2

A Material Review Board (MRB) is a

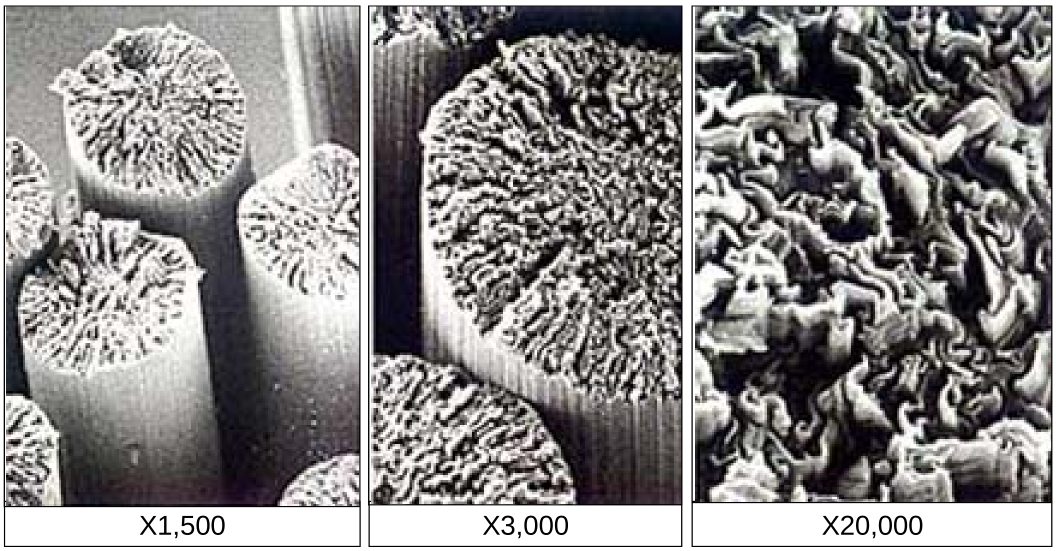
A. Board that looks at purchase orders concerning flight operations
B. Technical board assembled to assess damage and/or failure analysis results
C. Group that reviews components in a pressure system
D. Review board that approves material selections for space systems

COPV Manufacturing and Production

Fiber Production

Carbon Fiber

- Process
  - Part chemical
  - Part mechanical
- Advanced Composite Material Association established industry standards for carbon fiber



Carbon Fiber Microstructure

Carbon Fiber Terminology

- Filament
  - Long, continuous filaments
  - 0.0002 to 0.0004 in. diameter
- Tow (Roving, Strand)
  - Untwisted filaments
  - A large grouping of carbon fiber filaments packaged together onto a single spool. The term "small tow" refers to carbon fiber rovings that contain 24,000 or fewer filaments. "Large tow" refers to carbon fiber rovings that contain on the order of 48,000 to 320,000 filaments or more.
- Yarn
  - Multiple twisted tows (several thousand fibers)
- Tape
  - Multiple tow
  - Makes up ply angle
  - Full circuit makes up layer (often two plies)
- Structure
  - Multiple plies/layers
    - Ply angles cylinders (helical and hoop)
    - Ply angles sphere (polar and hoop)

Fiber Type Nomenclature

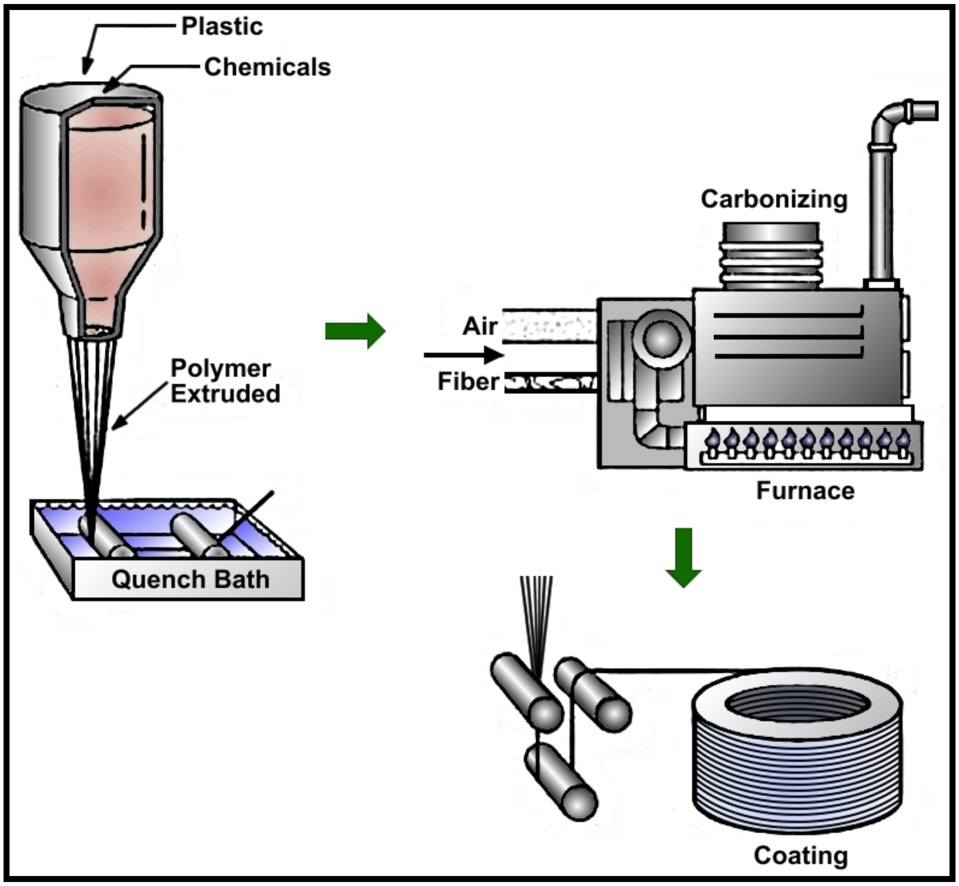
- Ultra-High Modulus (UHM)
  - 72 to 145 million psi
- High Modulus (HM)
  - 55 to 72 million psi
- Intermediate Modulus (IM)
  - 35 to 55 million psi
- Low Modulus
  - < 35 million psi
- Steel
  - 29 million psi

Fiber Production

- Main Precursors
  - Polyacrylonitrile (PAN)
  - Rayon
  - Pitch: residual petroleum product

PAN Process

- Polymerization
  - ~ 85 percent Polyacrylonitrile and 15 percent co-monomer
- Fiber Spinning
  - Spin solution (wet, dry-jet, dry, and melt)
- Stretching
  - Increase length up to 70 percent held during stabilization
- Stabilization
  - 180 to 300 °C
  - Cyclization, dehydrogenization, and oxidation
  - Clean room and pure oxygen
- Carbonization
  - 1,200 to 1,700 °C
  - Decrease pore size and increase strength in inert environment
  - Drives off non-carbon atoms and aligns carbon crystals
- Sizing and postheat treatment
  - Cures final fiber and minimizes pores
  - Oxidizes surface for adhesive bonding
  - Coats fiber to protect from damage



PAN Process

Comparison of Carbon Fiber and Steel

Material	Tensile Strength (GPa)	Tensile Modulus (GPa)	Density (g/ccm)	Specific Strength (GPa(ccm)/g)
Standard Grade Carbon Fiber	3.5	230.0	1.75	2.00
High Tensile Steel	1.3	210.0	7.87	0.17

Carbon Suppliers

- Toray Industries
- Toho Tenax
- Mitsubishi Rayon
- Hexcel
- Cytec Industries
- Schunk Gruppe

Health and Safety

- Dust inhalation
  - Protective masks (when dust present)
- Skin irritation
  - Protective clothing (when dust or loose fibers present)
- Electrically conductive
  - Isolated electronics (when dust or loose fibers present)
- Carcinogenic plume
  - Self-contained breathing apparatus (burn products are known to be carcinogenic)

Safe Handling

- Recommended Personnel Protective Equipment (PPE) requirements for burst COPV cleanup
  - Wet Cleanup
    - Leather gloves, lab coat, HEPA filter canister respirator, and suitable eye protection
  - Dry Cleanup
    - Leather gloves, a Tyvek suit with booties and hood, half face negative air pressure air purifying respirator outfitted with HEPA Filters, and protective splash goggles

COPV Manufacturing

COPV

- Complex Structure – various materials used together to construct a component
  - Metallic liner – material compatibility and hermetic sealing. Liner may carry load in some designs.
  - Fiber – Arimid fibers (Kevlar® and Zylon®), Carbon, or Glass carries majority of the load
  - Polymeric Matrix Resin – ensures proper fiber placement, facilitates load sharing, and provides protection.

PV Classification

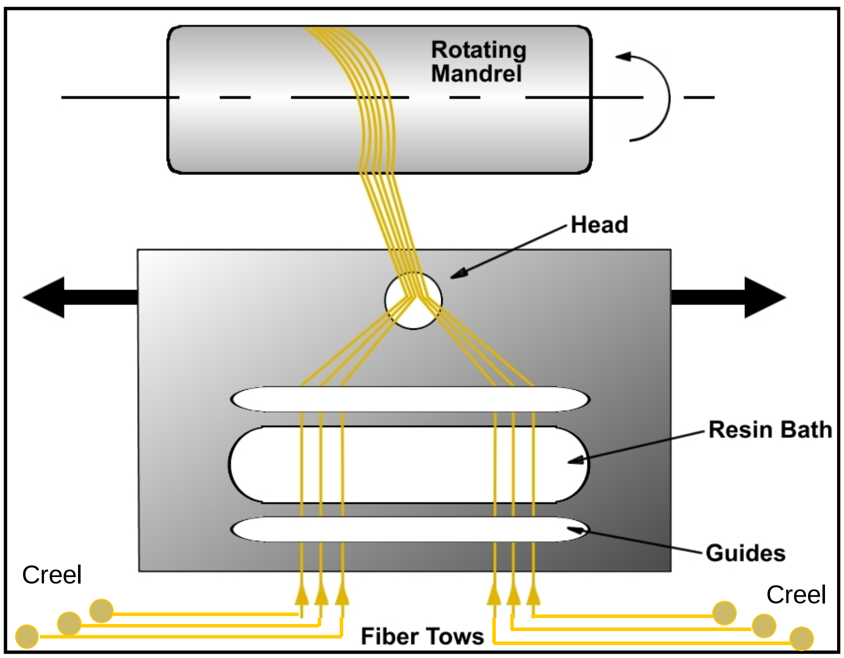
- Type I: All metal pressure vessel
- Type II: All metal w/ fiber wound hoop
- Type III: Metal liner completely overwrapped with fiber/resin system
- Type IV: No or non-metal liner completely overwrapped with fiber/resin system
- Type V: Lineless composite pressure vessel

COPV Production

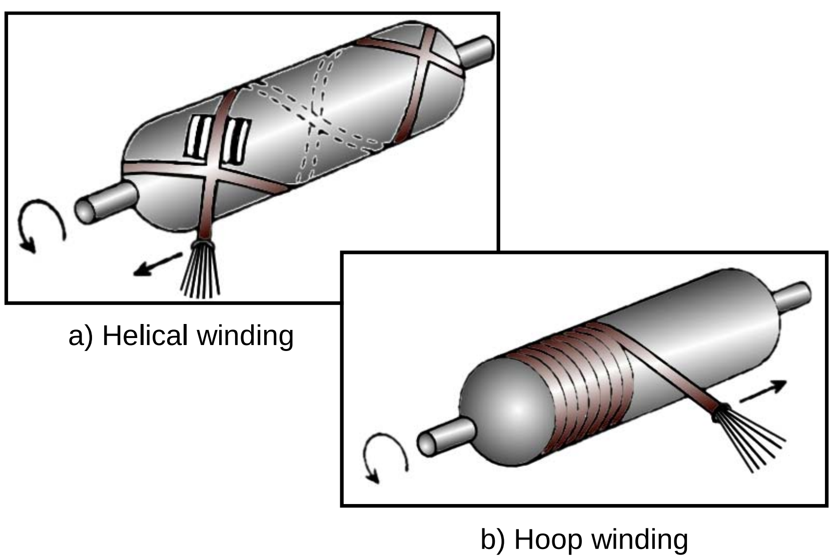
- Produce Fiber
- Apply Resin
  - Pre-impregnated fiber
  - Wet wind
- Apply Fiber/Matrix to Mandrel
- Cure Structure
- Autofrettage/Proof Vessel

Production Equipment

- Creel: loaded with fiber spools
  - Allows tow to be fed at constant tension to payout
    - wet wound or pre-impregnated with resin
- Comb: spreads tow to be applied to mandrel (liner is mandrel for COPV)
- Payout eye: keeps tow flat to produce a tape
- CNC machine: controls mandrel and creel to produce ply angles/layers
- Autoclave: cures resin to produce a complex anisotropic, laminate structure



Typical Wet Winding Process



Typical Cylindrical Wind Patterns

Winding Demonstration Video

COPV Manufacturers

- Arde
- Cobham
- General Dynamics (Brunswick/Lincoln Composites)
- Hypercomp
- ATK
- Structural Composites Industries

Filament Winding Pros/Cons

- Pros
  - Fast and economic
  - Resin Content
  - Fiber Cost minimized
  - Increase structural properties
- Cons
  - Limited to Convex shapes
  - Fibers not easily laid along length
  - Outer surface texturing
  - Lower viscosity resin for wet winding lower mechanical properties

Quiz # 3

What is the final procedure of COPV manufacturing?

A) Fiber production
B) Fiber winding
C) Structure proof
D) Structural cure

Damage Mechanisms

COPV Program Objectives

- Establish baseline strength
- Determine
  - Failure mode/safe life
  - Effects of impact damage and the consequences of long-term pressurized storage (1/2 year and >12 years)
- Evaluate
  - Materials compatibility with Aerospace fluids
    - Hypergols
    - Cryogens
    - Other (e.g. alcohol)
  - NDE techniques

COPV Program Test Articles

COPV Program Test Articles (Flight Qualified Design)

Vessel	Thickness Composite (in.)	Thickness Liner (in.)	Volume (in^3)	Mass (lbm)	MEOP (psi)	Proof (psi)	Ave. Burst (psi)
Large sphere	0.168	0.033	3157	24.5	4500	5650	7280
Small sphere	0.162	0.050	484	5.3	6000	7500	10,600
Large cylinder	0.147	0.040	2650	16.7	4500	5650	7850
Small cylinder	0.104	0.040	500	5.3	6000	7500	10,700

Baseline Burst Testing of Undamaged COPVs

Objective and Procedure

- Determine baseline burst strength and failure mode
  - Manufacturers' system/procedures vary
  - Baseline WSTF system/procedures
- Use DI water pressurization media
  - May cycle before burst

Results

Vessel	Design Burst Pressure (psi)	Actual Burst Pressure: Manufacturer (psi)	Actual Burst Pressure: WSTF (psi)
Large sphere	6750	7280	NA
Small sphere	9000	10,420	10,823[a] 10,472[b]
Large cylinder	6750	7774	7919[a]
Small cylinder	9000	10,882	10,508[b] 10,691[b]

NA = not available
[a]Burst test only
[b]Cycle, then burst

Small Sphere Undamaged Burst

Small Cylinder Undamaged Burst Video

Small Cylinder Undamaged Burst

Failure Mode/Safe Life Testing of Undamaged COPVs

Objective and Procedure

- Collect data for evaluation of failure mode and safe life predictions
  - Vessel designed to failure mode or safe life
    - Failure mode
      - leak before burst (LBB)
      - burst before leak (BBL)
    - Must prove safe life if COPV contains hazardous fluid or designed as LBB
- Compare cycling effect
  - Pneumatically vs. hydraulically
  - Flawed liner vs. unflawed liner

Results

- Small cylinders
  - Flawed Liner in hoop region
    - Pneumatically cycled: failed in 104 - 141 cycles
    - Hydraulically cycled: failed in 39 - 61 cycles
  - Unflawed Liner
    - Failed at 1279 - 1812 cycles at dome transition region
- Large sphere
  - Failed at 412 cycles

Summary

- All undamaged vessels exhibited LBB failure mode during cycling
- Small cylinders
  - Ductile failure mode
  - No fatigue striations
- Large sphere
  - Ductile failure mode
  - Fatigue striations
- Pneumatic vs. hydraulic cycling
  - Little effect

Overview of Impact Damage Effects Testing

Purpose of Testing

- To examine the effects of typical damage scenarios
  - Impact
  - Impact location
  - Impact insert geometry
  - Effect of pressurized state and media

Test Objectives

- Determine
  - Critical impact variables
  - Visual detection threshold
  - Critical impact energy (20% reduction in strength)
  - Pressurization media effects (H_2O & GN_2)
  - Effect of pressurized storage and impact
- Evaluate burst-pressure after impact

Critical Impact Variable

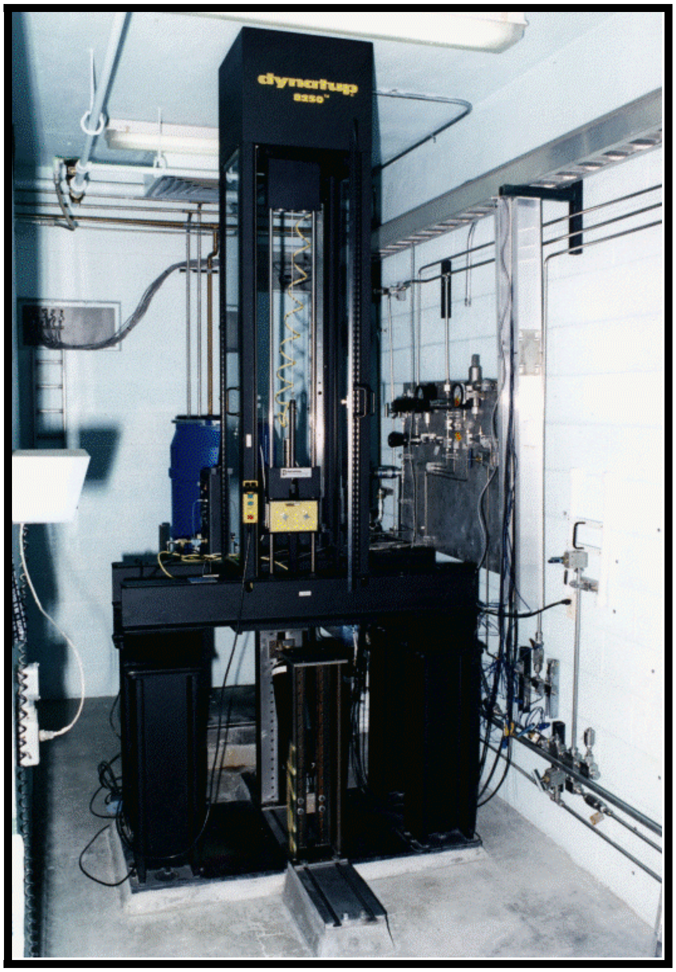
- Location on COPV
- Impactor geometry
- Multiple impacts
- Internal pressure
- Pressurant media
- Time at pressure after impact

Pretest NDE

- Manufacturers' records
- Visual inspection
- X-ray radiograph
- IR thermography

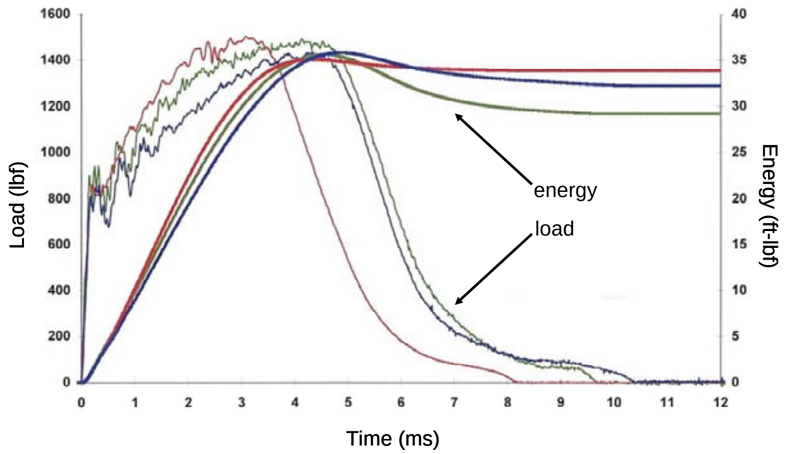
Posttest NDE

- Visual inspection
- IR thermograph
- Ultrasonic
- Eddy current
- Acoustic impedance testing
- Acoustic emissions while pressurizing



WSTF Impact Test System

Blast Enclosure



Typical Impact Curves

Small Cylinder Postimpact Burst

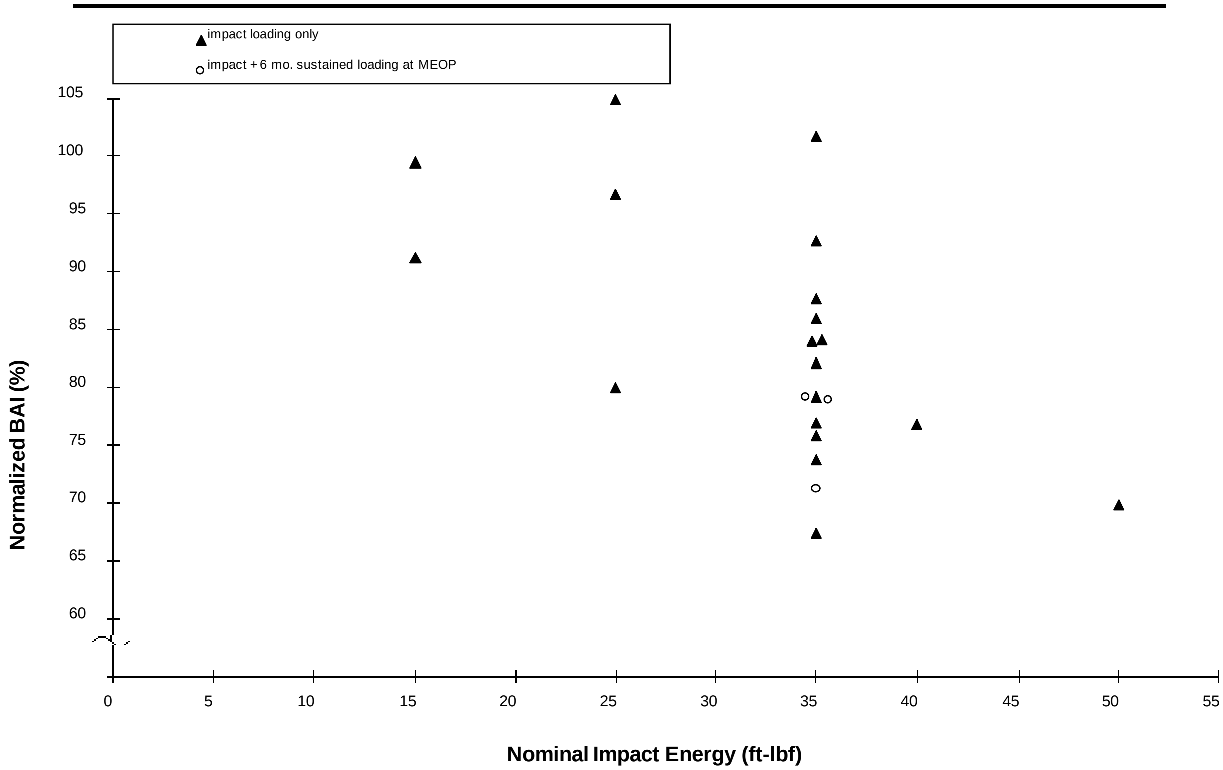
Small Sphere Postimpact Burst Video

CIE: 35 ft-lbf

MEOP: 6000 psig

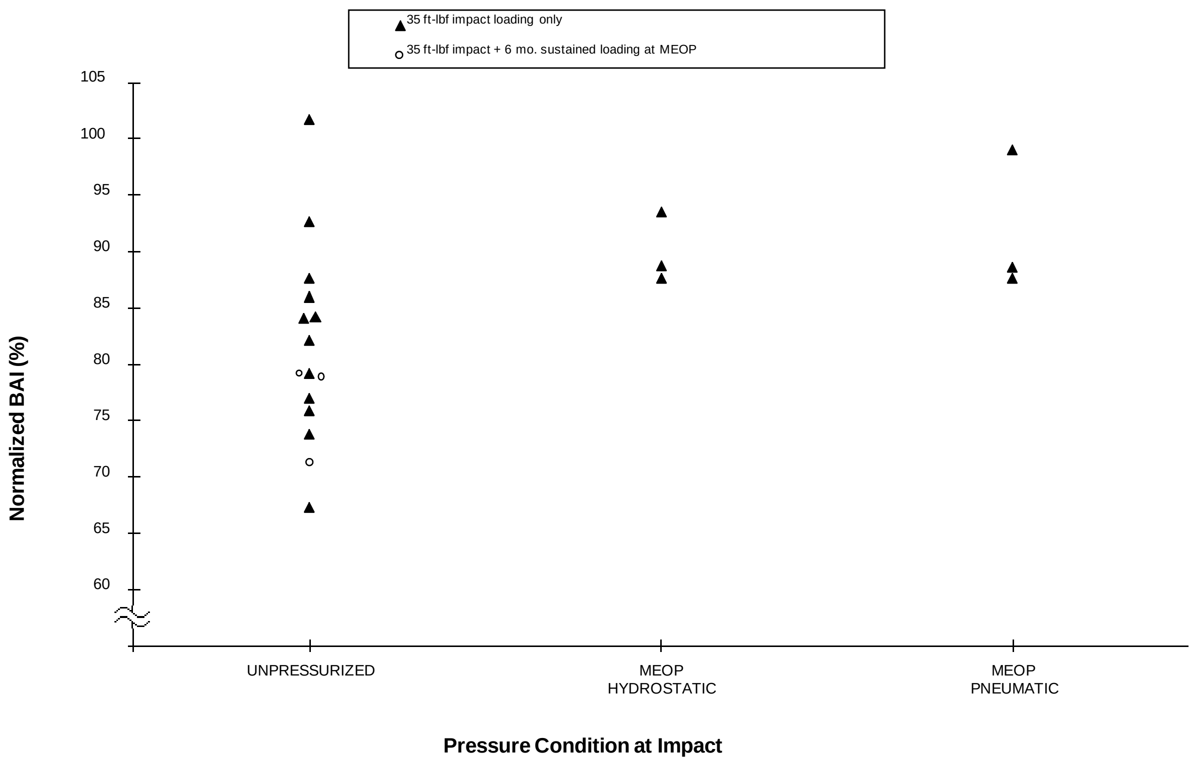
Undamaged $P_bV / W = 9.68 * 10^5$ in.

10.25 in. dia spherical COPVs



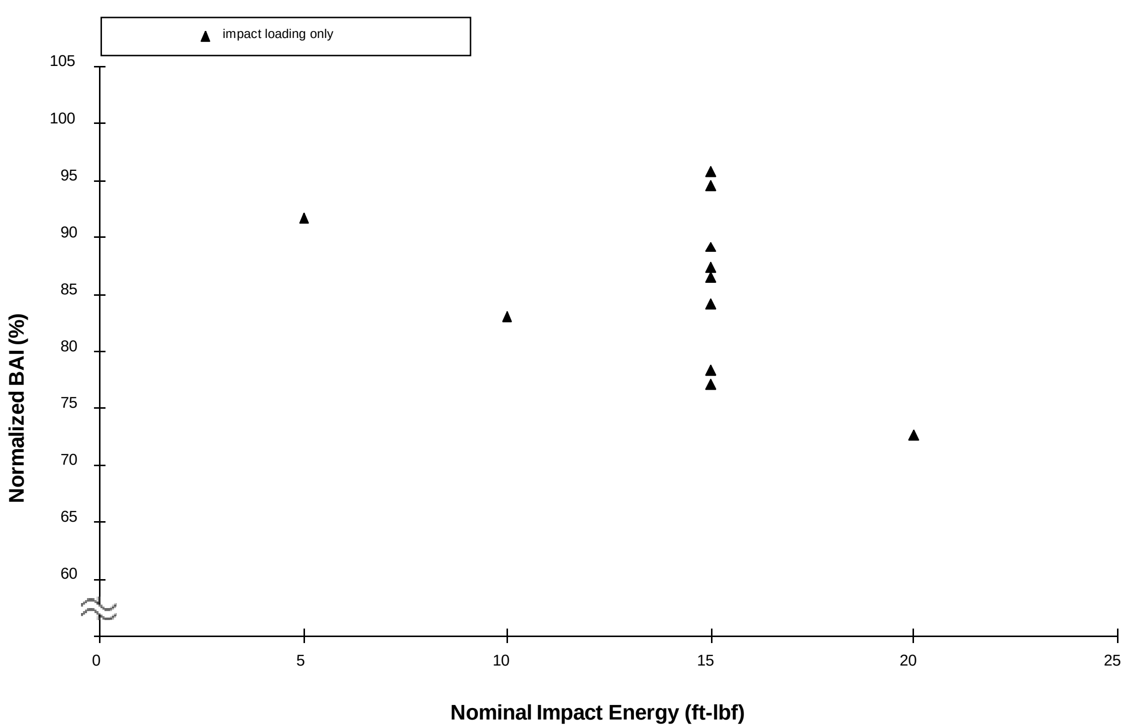
CIE: 35 ft-lbf
MEOP: 6000 psig
Undamaged $P_bV / W = 9.68 * 10^5$ in.

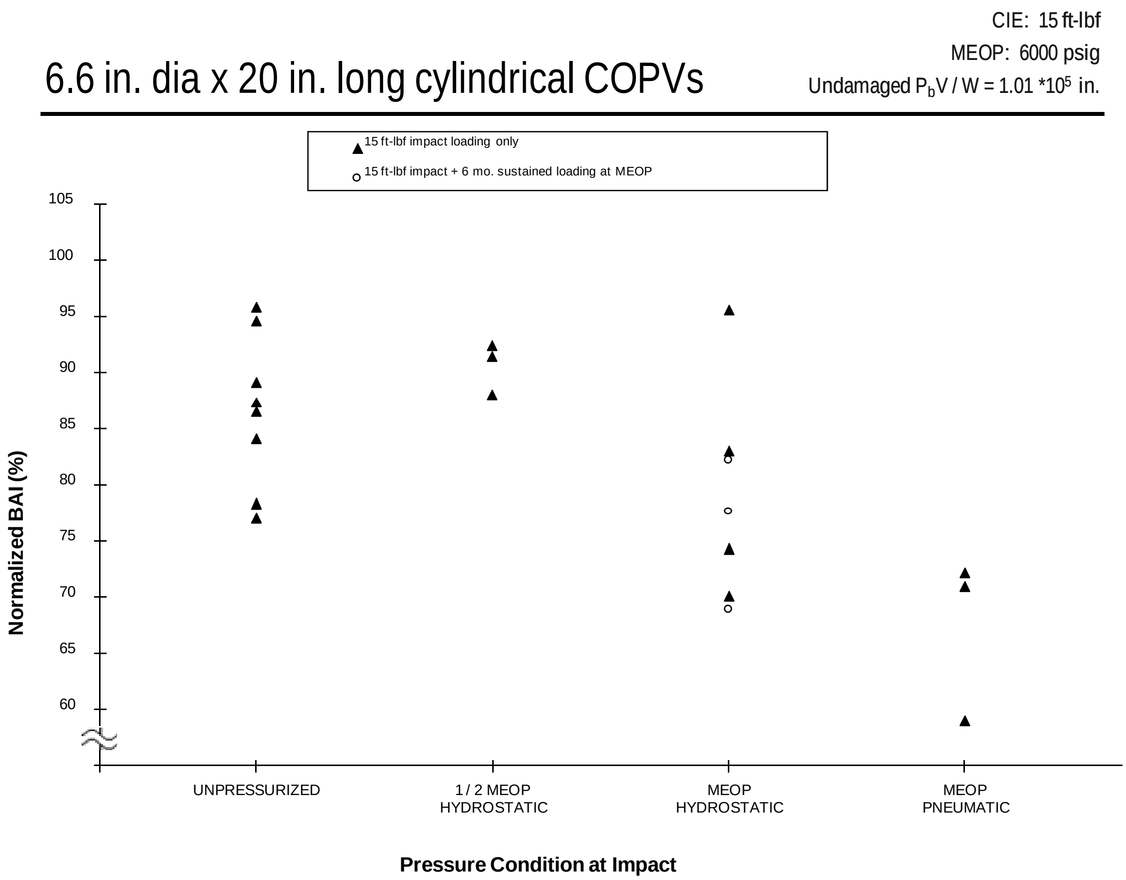
10.25 in. dia spherical COPVs

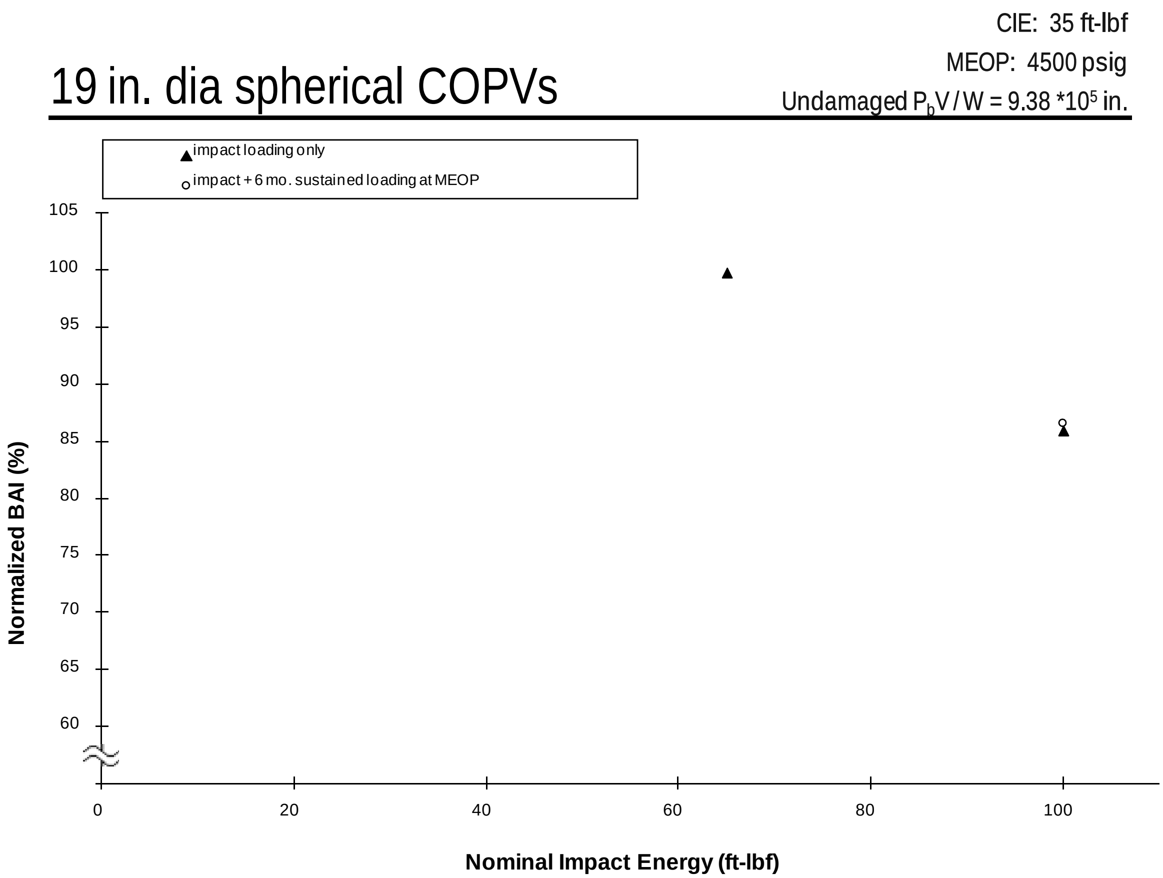


CIE: 15 ft-lbf
MEOP: 6000 psig
Undamaged $P_bV / W = 1.01 * 10^5$ in.

6.6 in. dia x 20 in. long cylindrical COPVs



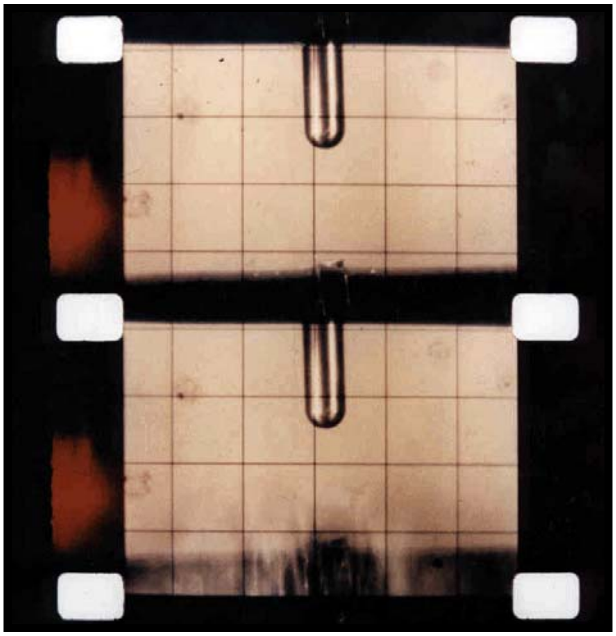

CIE: 15 ft-lbf
MEOP: 6000 psig
Undamaged $P_bV/W = 1.01 * 10^5$ in.
6.6 in. dia x 20 in. long cylindrical COPVs
15 ft-lbf impact loading only
15 ft-lbf impact + 6 mo. sustained loading at MEOP
Normalized BAI (%)
105
100
95
90
85
80
75
70
65
60
UNPRESSURIZED
1 / 2 MEOP HYDROSTATIC
MEOP HYDROSTATIC
MEOP PNEUMATIC
Pressure Condition at Impact


CIE: 35 ft-lbf
MEOP: 4500 psig
Undamaged $P_bV/W = 9.38 * 10^5$ in.
19 in. dia spherical COPVs
impact loading only
impact + 6 mo. sustained loading at MEOP
Normalized BAI (%)
105
100
95
90
85
80
75
70
65
60
0
20
40
60
80
100
Nominal Impact Energy (ft-lbf)

Impact Tests (Pneumatically Pressurized)

- Impacted small cylinder at VDT level with COPV pressurized to MEOP
  - ½ in. Hemispherical tup insert
  - Single 15 ft-lb impact
  - Gaseous nitrogen (6,300 psig)
- Two vessels impacted and BAI determined
  - Approx. 7500 psi burst pressure
- One vessel burst in test stand 0.7 s after impact
  - Catastrophic failure

Pneumatic Burst upon Impact Video



Damage after Pneumatic BUI

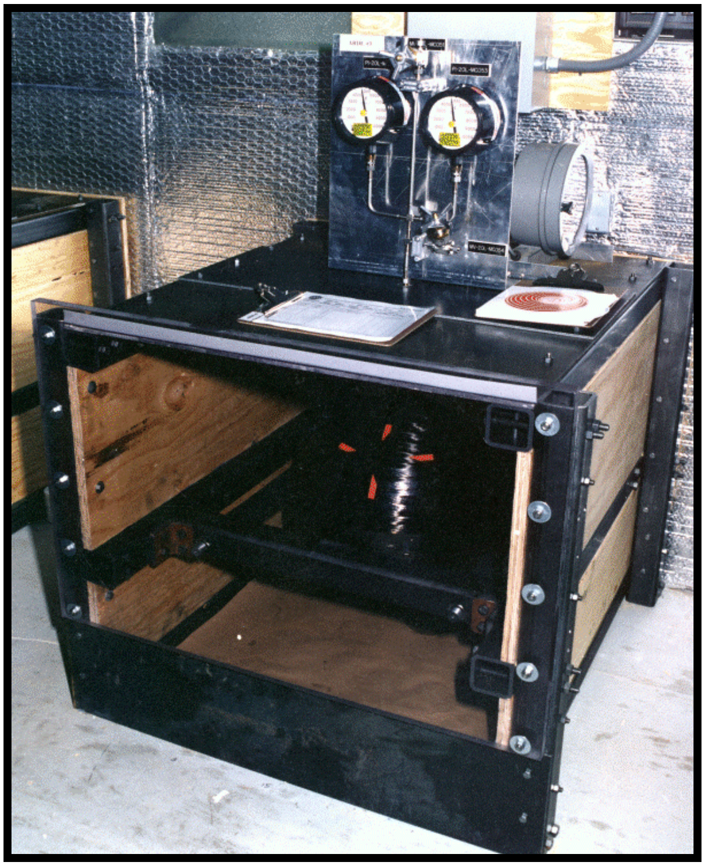
Pneumatic BUI Vessel Posttest

Effects of Pressurized Storage and Impact

Objective and Procedures

- Study combined effects of CIE impact damage and sustained load
- Perform
  - CIE impact of flight COPVs
  - 6-month testing at COPV MEOPs
  - Burst test all COPVs surviving after 6 months pressurized storage

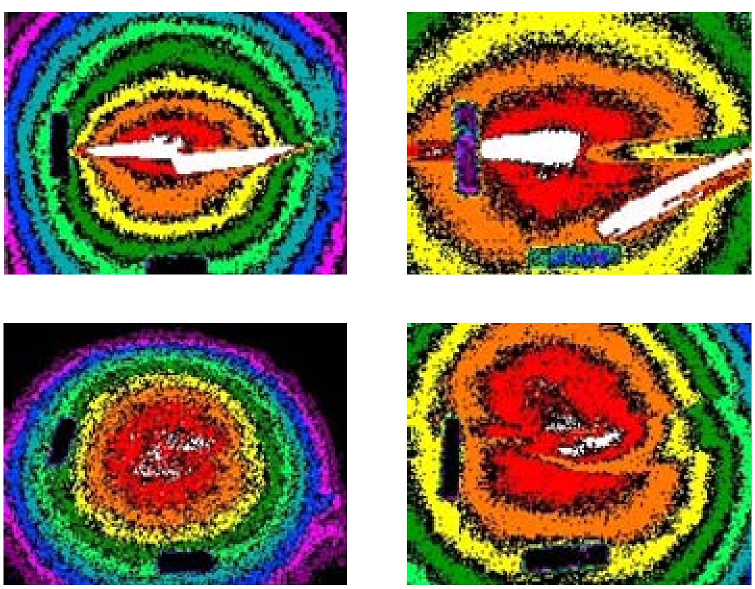
NOTE: simulates a COPV damaged and pressurized on the pad



Vessel Enclosure for Long-term Storage

IR Thermography

Before sustained loading | After sustained loading



13 x 25 in. cylinders
4500 psi hydrostatic impact
0.5 in. dia hemispherical tup
35 ft-lbf

19 in. dia spheres
4725 psi pneumatic impact
0.5 in. dia hemispherical tup
100 ft-lbf

Damage Growth During Six-month Test

Results (6-Month Sustained Load)

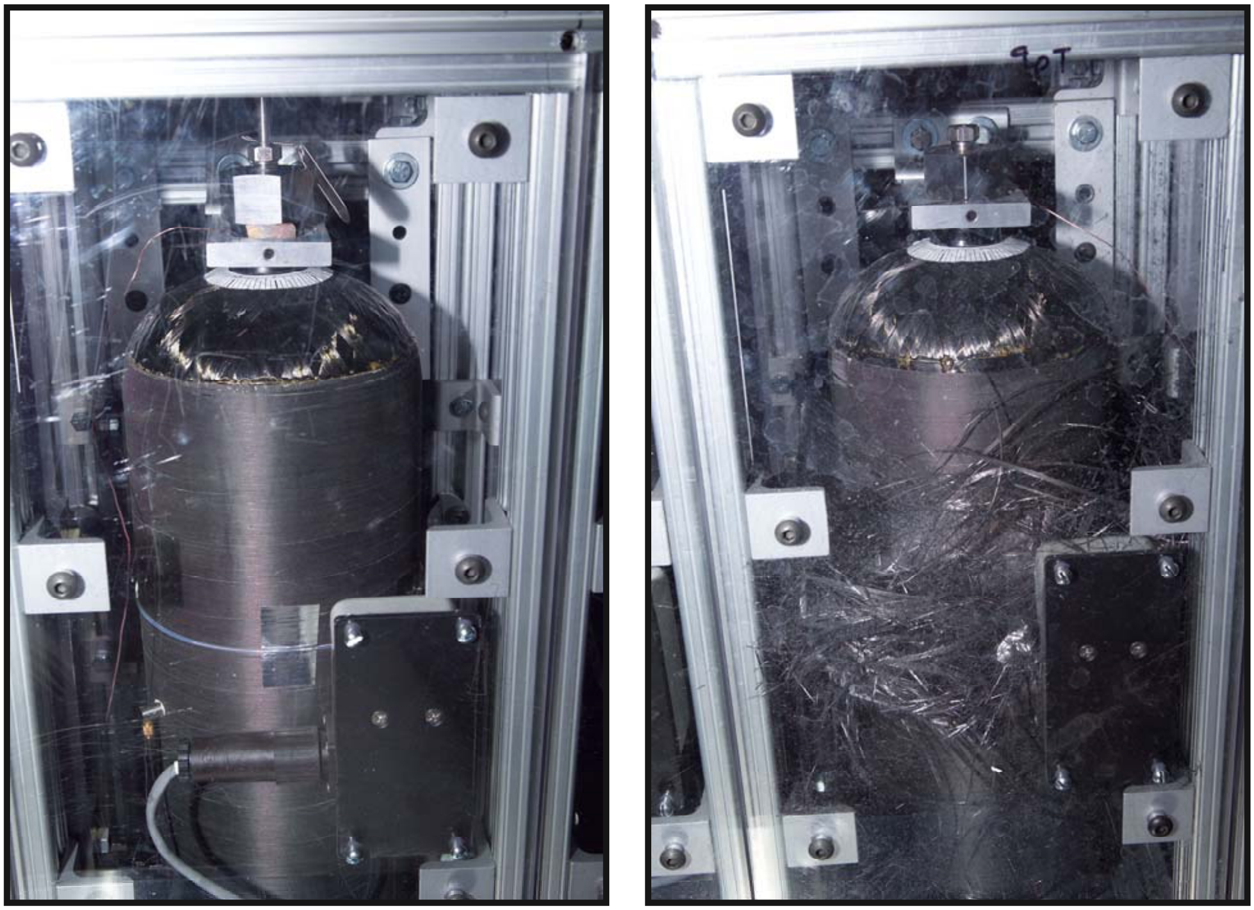
Vessel	Impact Condition (psi)	Impact Energy (ft-lb)	Average Burst (psi)
Large sphere	4725 pneumatic	100	6142
Small sphere	Unpressurized	35	8103
Large cylinder	4500 hydrostatic	35	6079
Small cylinder	6000 hydrostatic	15	8156

Summary

- Damage growth observed during longer term pressurized storage
- Damage growth appears superficial
- No pressurization effect on BAI observed (6 month test duration)
- Multiyear tests in progress
  - > 12 years in testing

Stress Rupture Testing

- Examine affects of sustained load on a composite structure
  - NNWG program to track progressive stress rupture and monitor with various NDE
  - Various fiber types
  - Multiple stress ratios
  - On-going program with multiple campaigns



Stress Rupture Facility

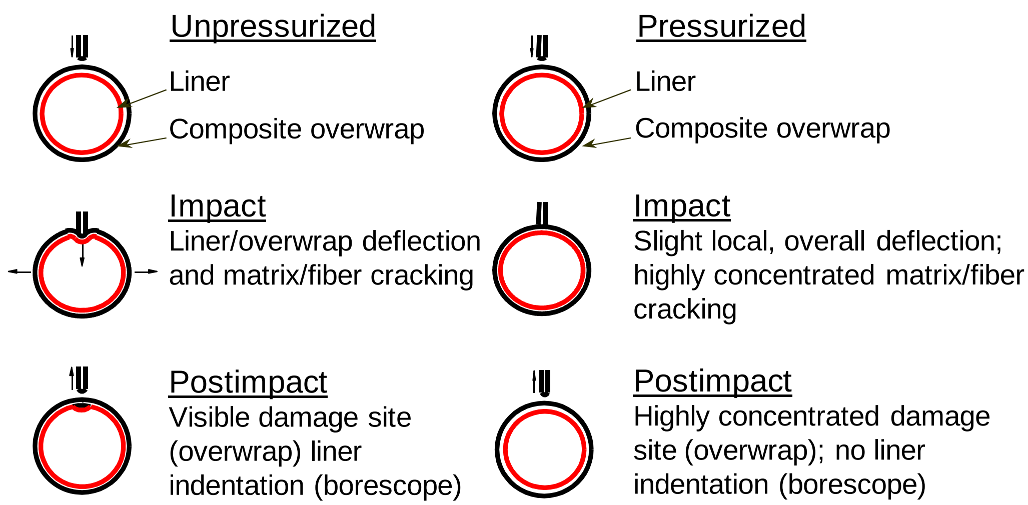
Impact Damage Summary

Impact Damage Susceptibility

- High susceptibility to impact damage
- Large variance (6%) in BAI
- Significant influence parameters
  - Impact energy
  - Impact geometry
  - COPV geometry/design and ply lay-up
  - COPV pressure state

NOTE: Reiterates need for impact control plan

COPV Cross Section



Impending Impact

Qualitative NDE Assessment

- Visual and acoustic impedance provide first indications of impact damage
- IR thermography and UT for more diagnostics of identified site(s)
- Multiple NDE methods improve ability to detect and understand damage state
- All important information to assist MRB assessment of residual strength state

Impact Control Plan

- Perform credible threat analysis for “cradle-to-grave”
- Establish VDT & IDT for COPVs
- Implement indicators and/or protectors
- Train visual inspectors to detect mechanical damage
- Designate inspection points

Future Work

- Other fibers (Zylon®)
- NGV/HGV (DOT-rated COPVs)
- Plastic-lined COPV (Type IV)
- Unlined composite pressure vessels
- Large propellant tanks with ultrathin liner and overwrap
- Structural composite tanks for launch vehicles
- Improved NDE technology
  - Flash thermography
  - Laser shearography
- Improved modeling techniques
- Crack indexing for quantitative evaluation

Ascent Abort COPV Testing

- WSTF dead weight tester to inflict damage
- Dedicated test article to identify VDT
- Tested individual COPVs to worse case and VDT impact damage per AIAA S-081A, 6.1
  - Approach C: Worst-Case Threat Damage Tolerance Testing
  - Approach D: Visual Mechanical Damage Threshold Testing
- Burst tested each COPV to determine reduction in strength

Impact Results

- Impactor geometry:
  - 1/2 in. hemi tup
  - 1/8 in. radius guillotine
- VDT: 1/2 in. hemi tup = 10 ft-lb
- VDT: 1/8 in. radius guillotine = 15 ft-lb
- Worse Case Credible Threat:
  - 1/2 in. hemi tup @ 35 ft-lb = 44 ft-lb

Burst Results

- Nominal burst: 14,300 psia
  - Approach C: 15,565 psi
    - 1/8 in. radius guillotine 15 ft-lb
    - 1/2 in. Hemi tup 10 ft-lb
  - Approach D: 14,600 psi
    - 1/2 in. Hemi tup 44 Ft-lb impact

Impact/Burst Photos

Materials Compatibility Testing

Objectives

- Determine effect of exposure to aerospace fluids on COPV strength
- Correlate coupon level and component level burst test results

Materials - Coupon Testing

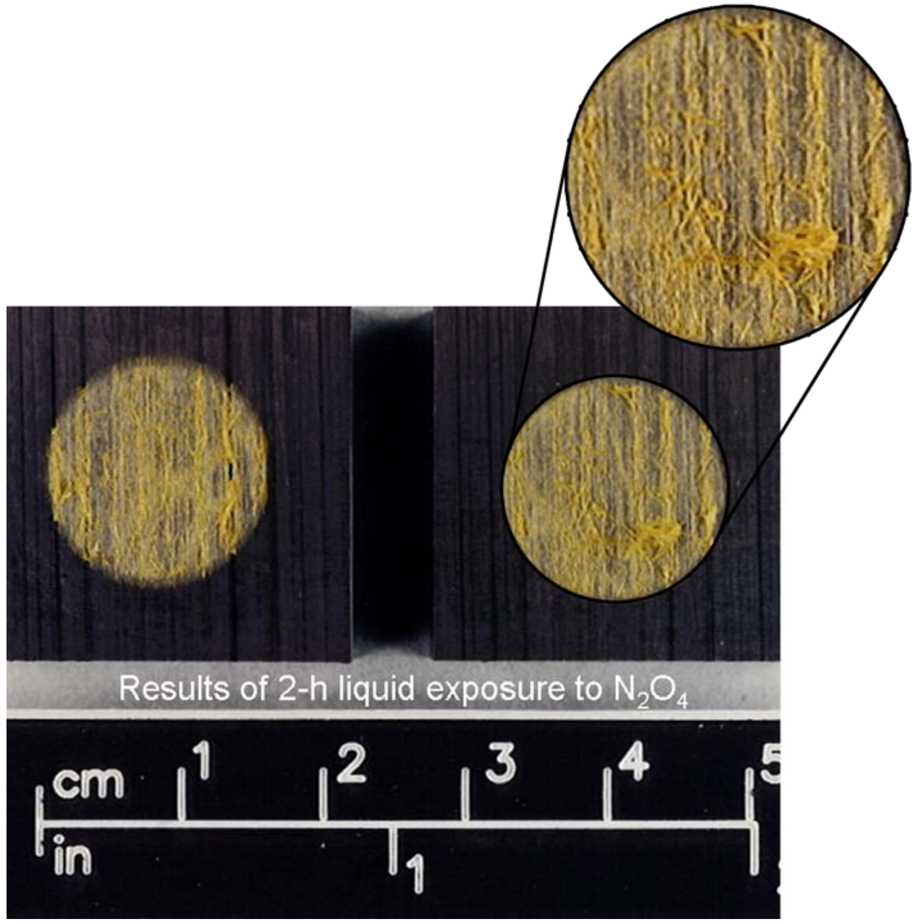
- Fluids
  - Hypergols
    - Hydrazine fuels (N_2H_4, MMH, UDMH)
    - Oxidizer (N_2O_4, liquid and vapor)
  - Cryogens (LOX, LN_2)
  - Others (RP-1, IPA)
- Coupons
  - SCI Gr/Ep (SCI REZ100 w/ Toray T-1000)
  - Lincoln Gr/Ep

Procedure - Coupon Testing

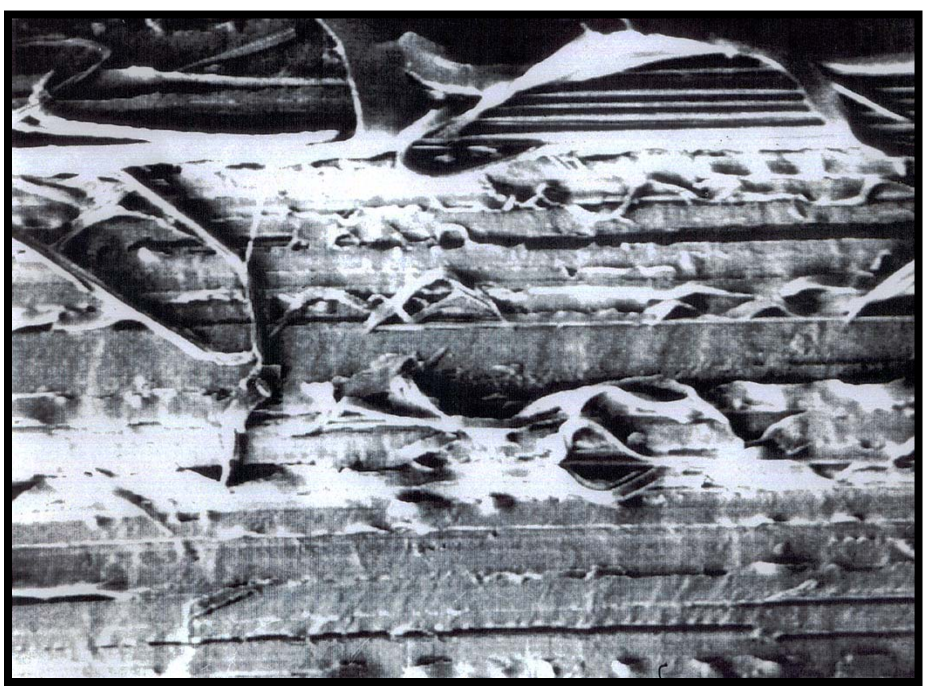
- Immersion
  - Soaked in LOX prior to impact
- Impacted by Instrumented Mechanical Impact tester (IMIT)
  - Anvil backed
  - ½ in. Hemispherical Tup insert
- Reactive in LOX mechanical impact tests (Impact sensitive)
- Immersion
  - 2 h and 8 h, ambient pressure
- Drip
  - 5 mL/h, 2 h, ambient pressure
- Vapor
  - N_2O_4-saturated, 2 h, ambient pressure

Results - Coupon Testing

- Visual
  - Minor surface dulling with fuels
  - Yellow oxidizer/matrix reaction product
- No significant strength loss or modulus change



NTO Coupon Damage



NTO Coupon Damage Detail

Materials - COPV Testing

- Fluids
  - Hydrazine fuels (N_2H_4, MMH, UDMH)
  - Oxidizer (N_2O_4)
  - Cryogens (LOX, LN_2)
- Vessels
  - SCI Model AC 5229 cylinders
    - 4 in. dia x 9 in. long MEOP 3500 psi, burst 7000 psi
  - Lincoln Model 220088-1 spheres
    - 10.25 in. dia sphere MEOP 6000 psi, burst pressure of 10,600 psi

Procedure - COPV Testing

- Pressurize to 95% MEOP
- Expose hemisphere to liquid, 2 h
- Depressurize and field decontaminate (water rinse)
- Optional - Air dry for 24 h (no rinse)

COPV Exposure Results

SCI Subscale Vessels in Fuels

Exposure Condition	Burst Strength (psi)	Deviation form Nominal Burst
Baseline	7625	250
Hydrazine, 2 h	7350	300
Hydrazine, 2 h, 24 h dry	7300	270
MMH, 2 h	7590	270
MMH, 2 h, 24 h dry	7525	70
UDMH, 2 h	7500	420
UDMH, 2 h, 24 h dry	7630	390

SCI Subscale Vessels in Oxidizer and Cryogens

Exposure Condition	Burst Strength (psi)	Deviation form Nominal Burst
Baseline	7200	340
N_2O_4, 2 h	7620	650
N_2O_4, 2 h, 24 h dry	7540	700
Liquid oxygen, 2 h	6960	120
Liquid nitrogen, 2 h	7020	240

Small Sphere

Exposure Condition	Burst Strength (psi)
Baseline	10,600
Hydrazine, 2 h	11,500
N_2O_4	10,500
Liquid oxygen	10,600

SCI Subscale Vessel after N_2O_4 Exposure

Summary

- Superficial or insignificant effect of exposure on coupons, including oxidizer
  - Weight, hardness, flex strength
- Propellants had no effect on burst strength of the COPVs tested

Quiz #4

Which aerospace fluid has an effect on Gr/Ep COPV strength?

A. Oxidizer
B. Fuel
C. LOX
D. None of the above

Damage Progression

COPV Damage

- COPVs are susceptible to impact damage
  - High modulus fibers are weak in shear
- Residual strength after damage is vital
  - Potential go/no-go factor (S&MA)
- Impact damage may be difficult to discern by untrained eye
  - Currently, residual strength cannot be quantified by any one NDE method

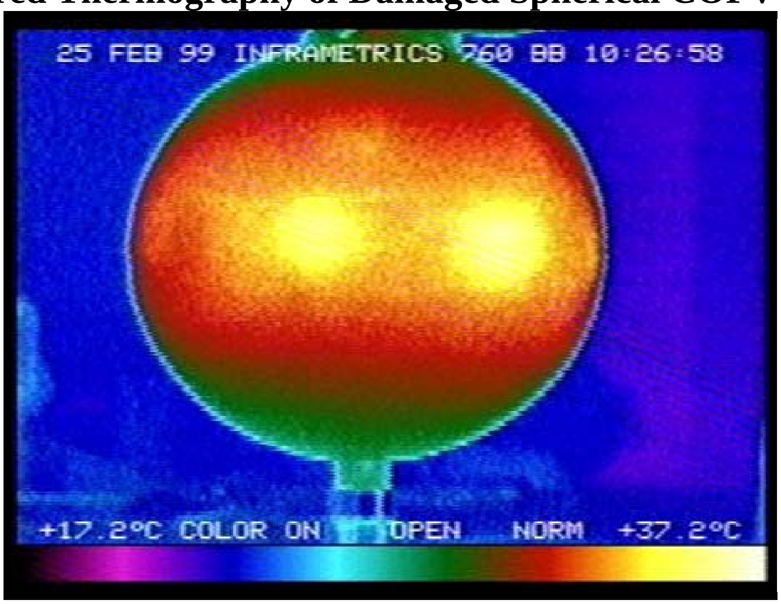
Composite Materials

- Composite structures behave differently
  - Non-homogeneous materials
    - Metallic liner
    - Fiber
    - Matrix
  - Anisotropic lamina/laminates
    - Function of constituents and ply properties
    - Coupling effects (shared load)
  - Progressive damage

Damage Quantification

- NDE identifies damage location and general extent, but cannot discern subsurface fiber damage
- Destructive evaluation can identify fiber fractures (Crack Index) and ply delamination
  - Thermal deply analysis
    - Crack index

Video of Infrared Thermography of Damaged Spherical COPV



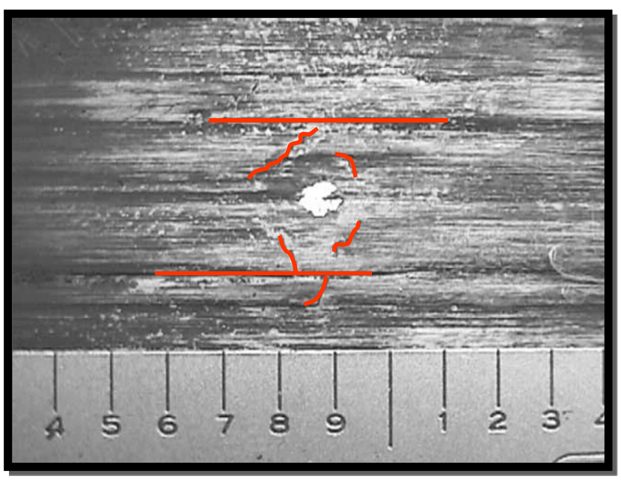
Progressive Damage Phenomena

- Unique behavior of composites
  - Load redistribution with damage accumulation
    - Material properties of structure continually change as constituents “fail” and load is redistributed
- Example of damage progression
  - Matrix cracking in Plies 2 and 4
  - Delamination between Plies 3 and 4
  - Fiber fracture in ply 3

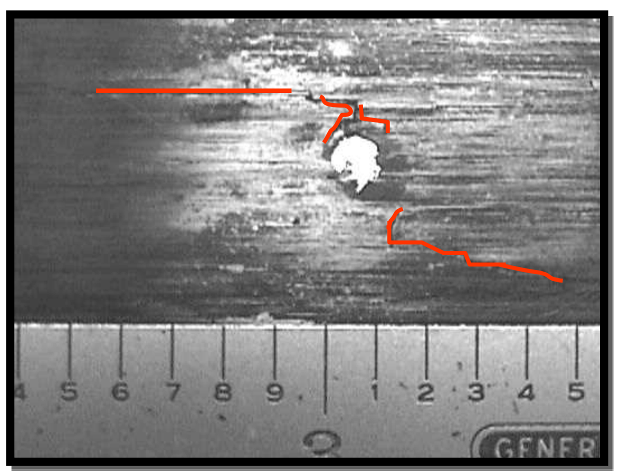
Thermal Deply Results

Thermal Deply Analysis Technique

- Impact COPV using IMIT
- Section COPV impact zones into 4 x 4 in. coupons
- Soak impact zone in AuCl/ether solution
- Pyrolyze coupons to remove matrix
- Deply coupons ply-by-ply
- Document damage ply-by-ply

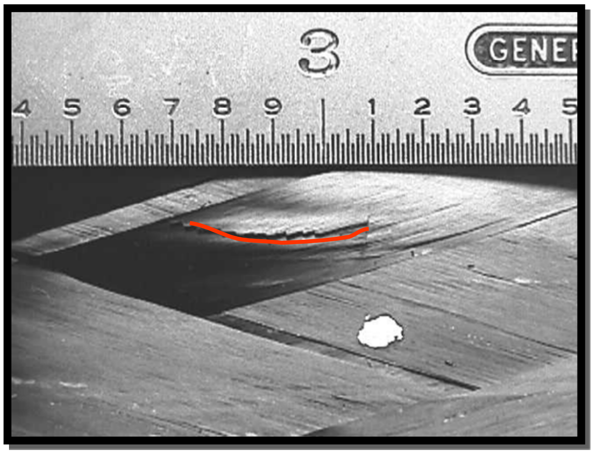


15 ft-lbf impact

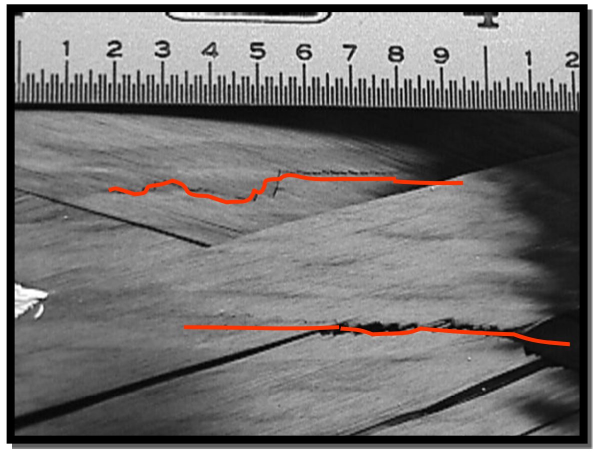


40 ft-lbf impact

Surface Impact Damage

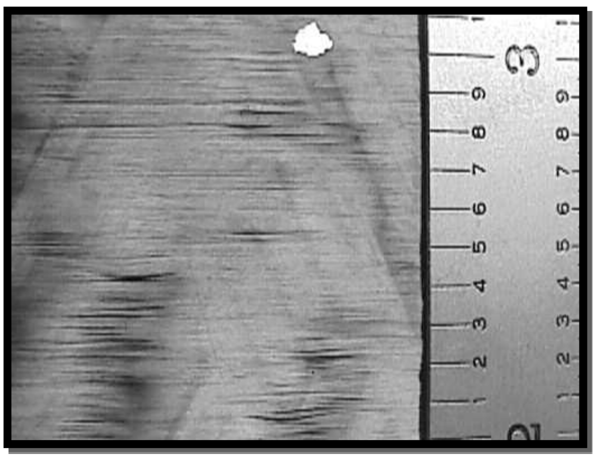


15 ft-lbf impact

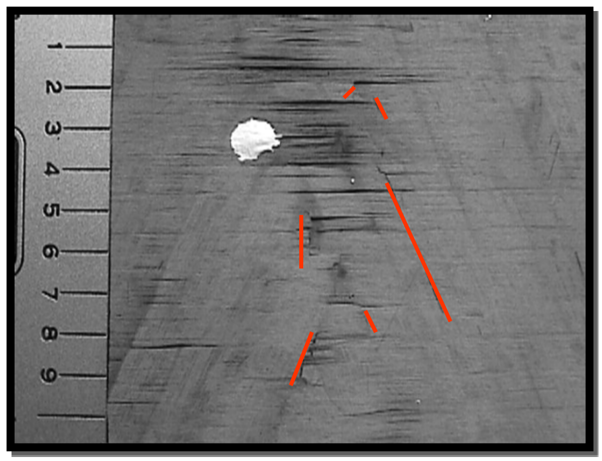


40 ft-lbf impact

Ply 2 Impact Damage

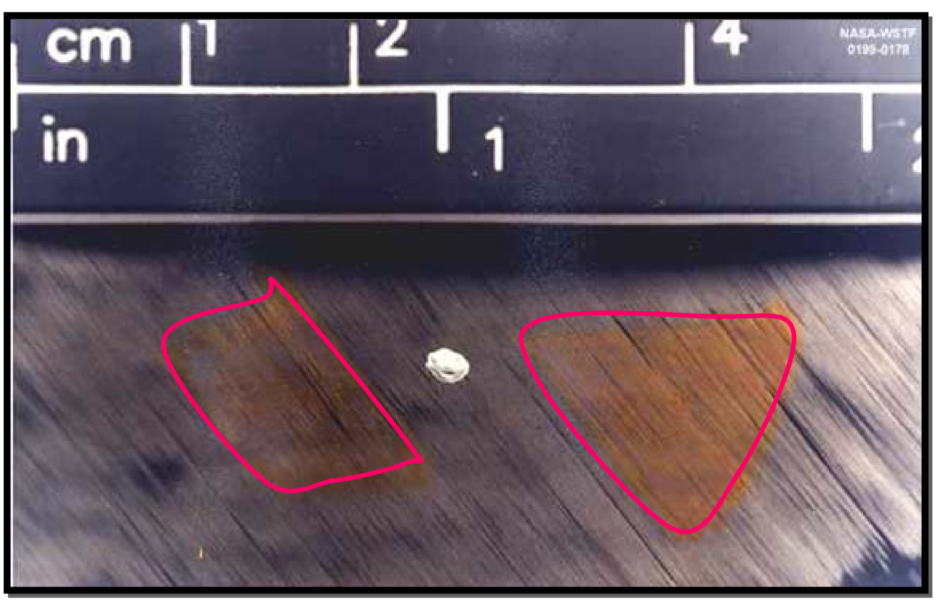


15 ft-lbf impact

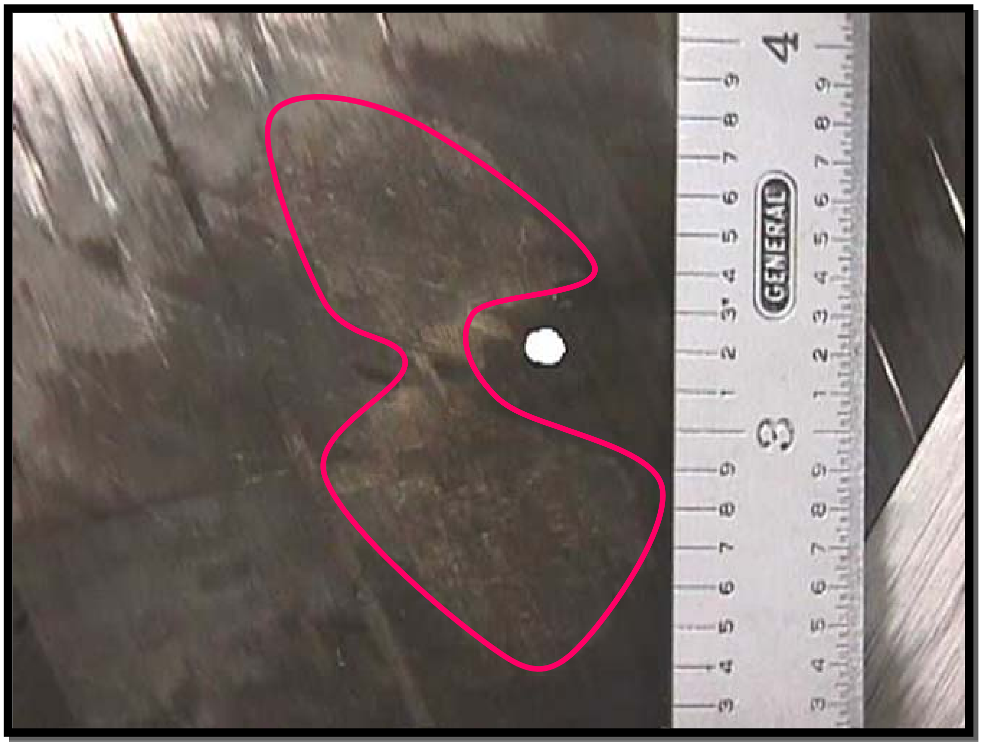


40 ft-lbf impact

Ply 4 Impact Damage



Delamination Zone Between Plies 3 and 4 (20 ft-lbf impact)



Delamination Zone Between Plies 2 and 3 (20 ft-lbf impact)

Crack Index

- Quantitative measure of the extent of fiber damage (no units)

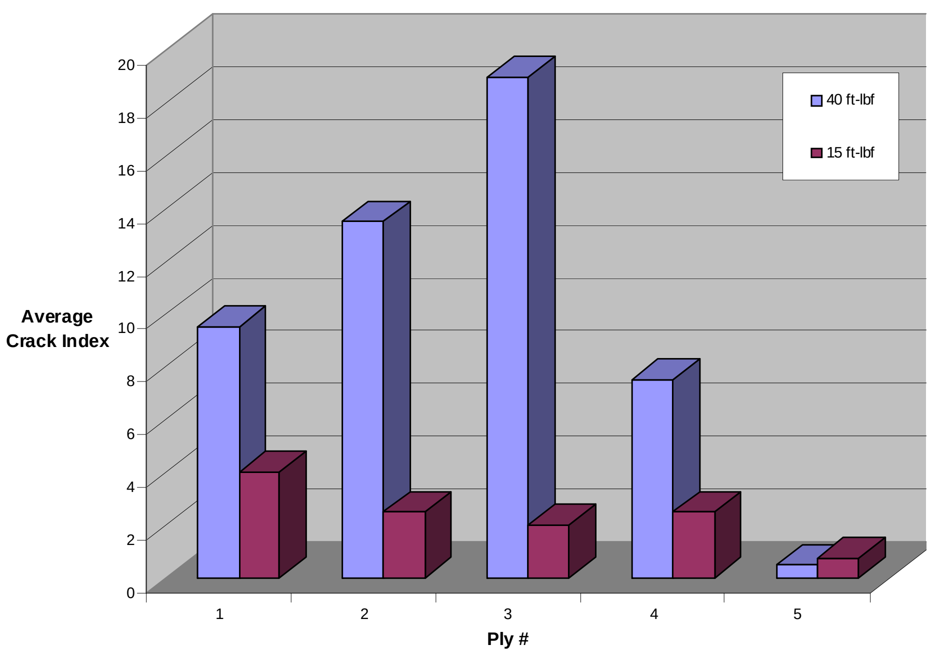
Crack Index=(sum of small cracks) + (sum of medium X2) + (sum of large X5)

where

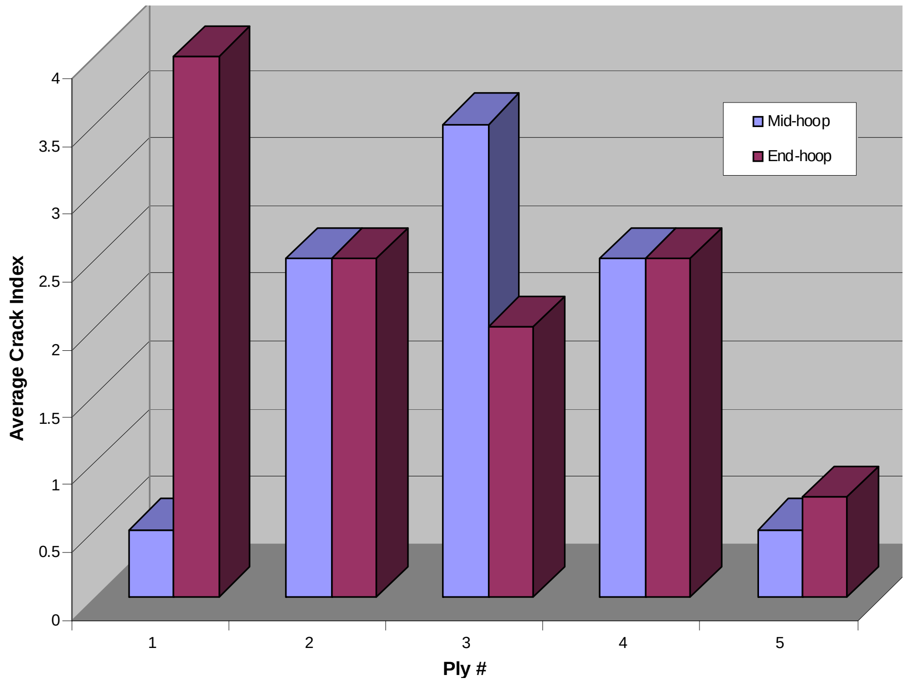
small = crack length < 0.1 in.

medium = 0.1 in. < crack length < 0.5 in.

large = crack length > 0.5 in.



Crack Indices of Various Energy Impacts



Crack Indices of Various Impact Locations (Cylinders)

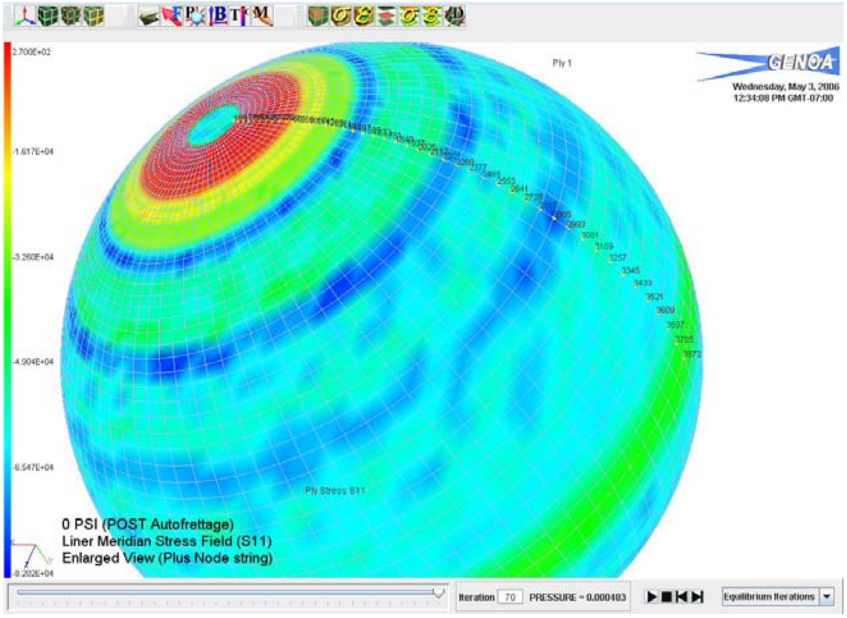
COPV Finite Element Analysis (FEA)

- Commercial and Proprietary Methods Available
  - Manufacturer (Initial Design Models)
    - Either Commercial or 'In-House' codes are typically used
    - Normally protected\proprietary information
  - Independent Verification Methods
    - Composites Oriented Package
      - GENOA PFA w/MHOST FEA Solver
    - General FEA w/composites capability
      - ANSYS
      - ABAQUS
      - NASTRAN
      - LS-Dyna
    - 'Mainframe' Codes

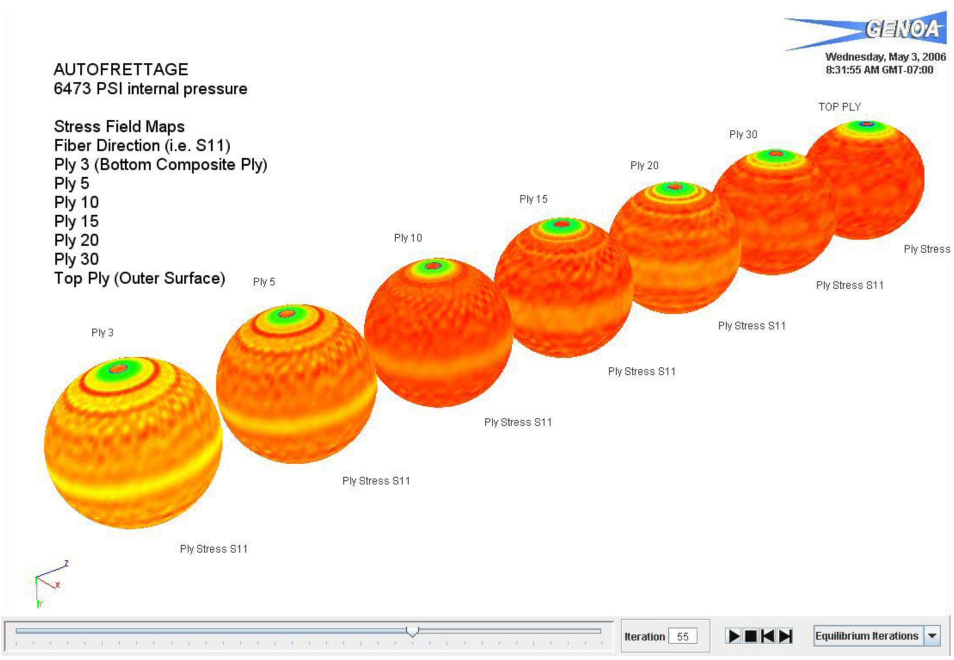
COPV FEA Modeling at WSTF

- Genoa - PFA (General Optimization and Analysis -Progressive Failure Analysis)
  - Nonlinear\Linear static and dynamic FEA of laminated polymer composites typically used for COPVs
  - Base Core Codes Developed at NASA GRC (LeRC)
    - CODSTRAN (Composite Durability and Structural Analysis)
    - ICAN (Integrated Composite Analyzer)
  - Constituent damage and progressive fracture based on multiple criteria
  - Stepwise solution technique (Progressive)
  - Commercially available at AlphaStar Corp. (Long Beach, CA)
- Genoa modeling objectives
  - Correlate NDE data with a damage state, predict BAI
  - Correlate Surface Stress/Strain observations to internal composite mechanics
  - Verify manufacturer's models/predictions

Examples –Stress States



Liner Compressive Stress Post Autofrettage (0 psi Internal Pressure)



"Proof" Pressure Stress at Various Depths in Composite

Examples – Damage Prediction

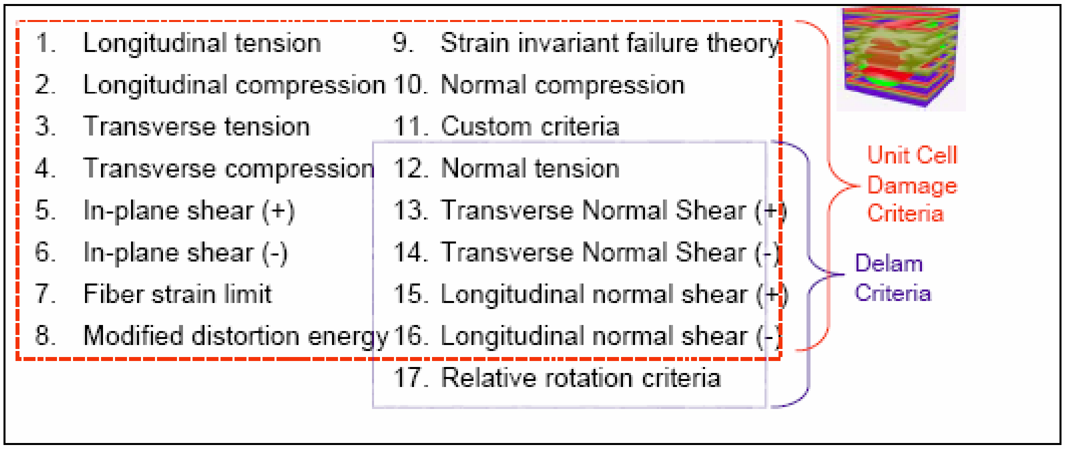
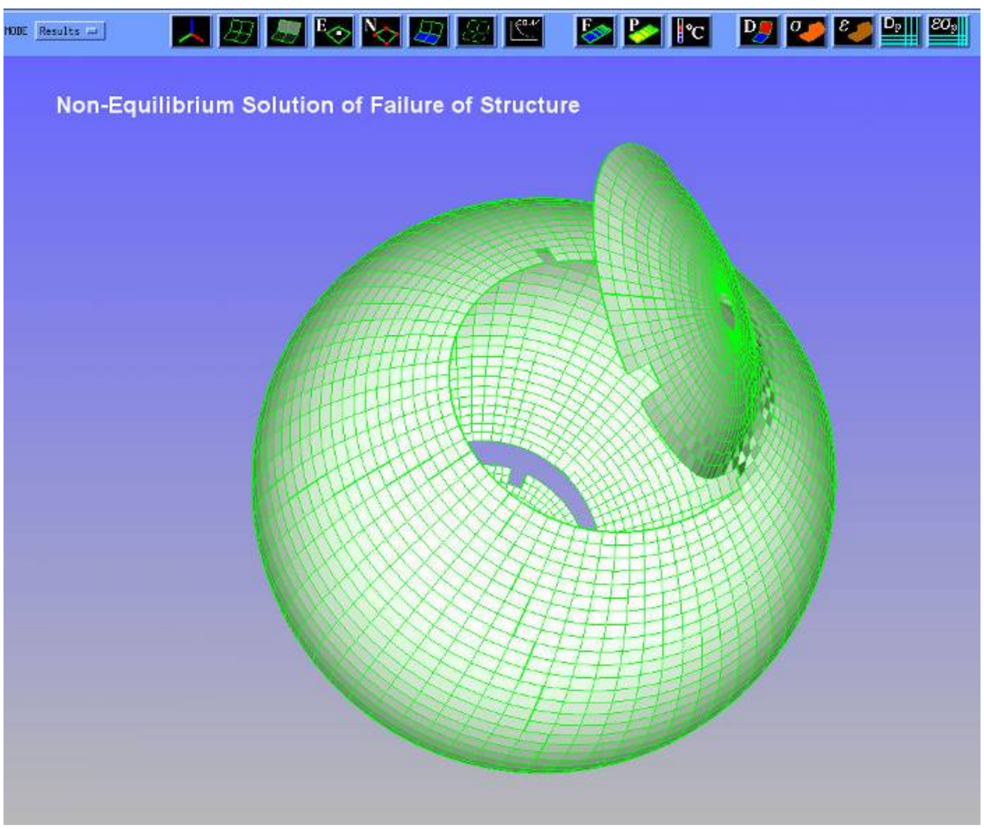


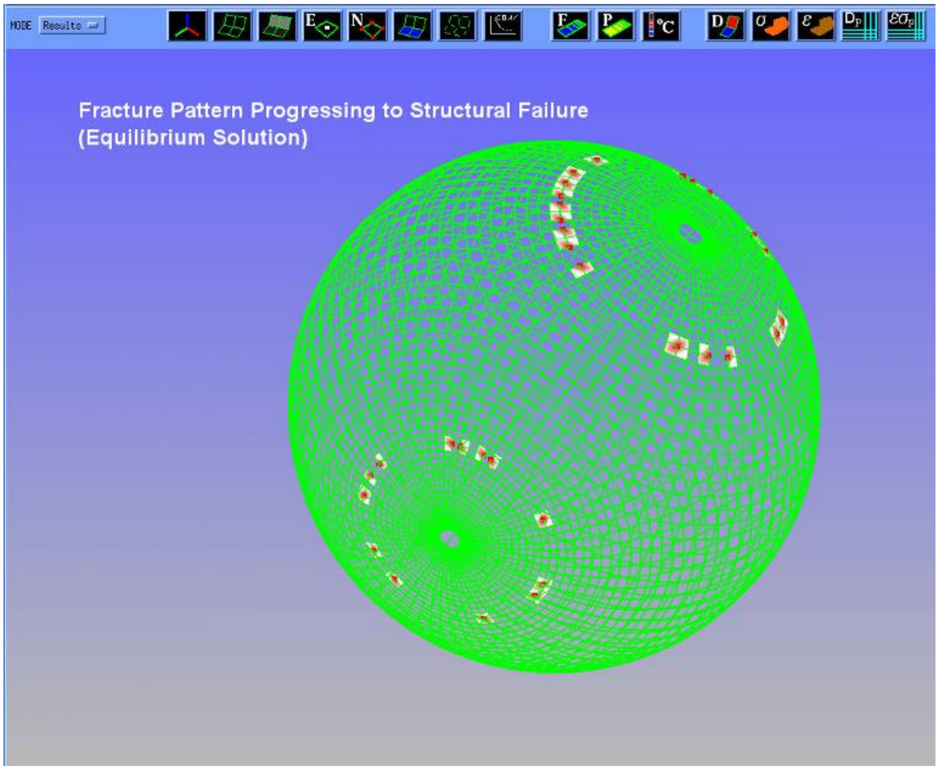
Figure 1 Unit cell and De-lamination failure criteria

Reference

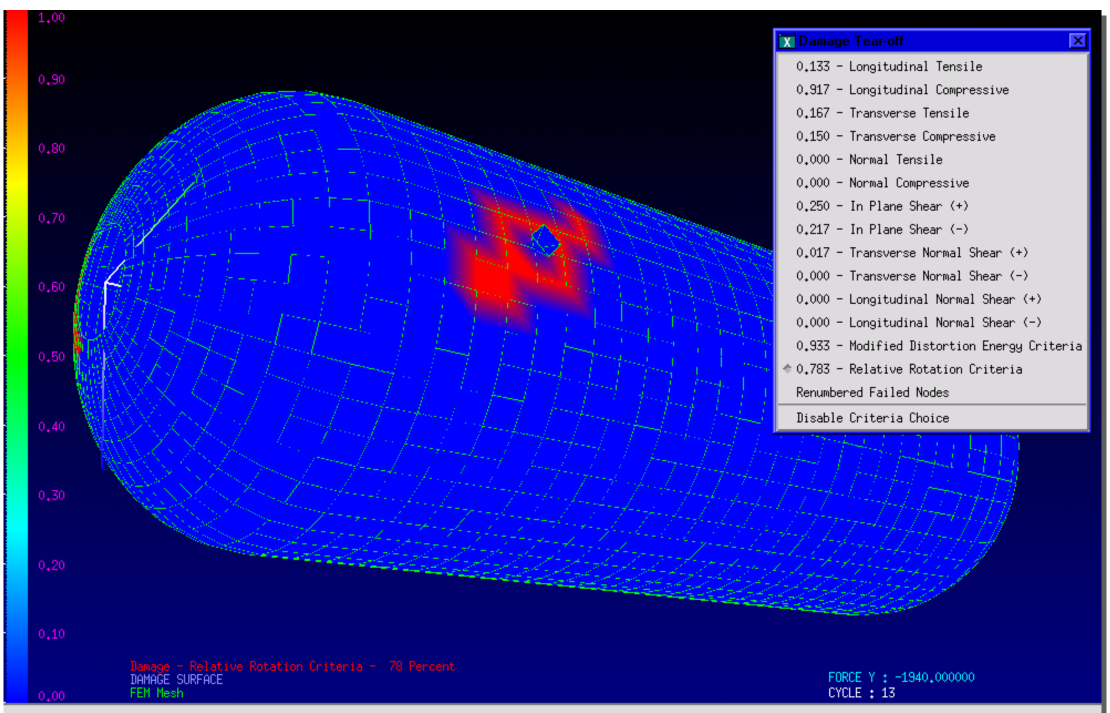
Frank Abdi, Dade Huang, Ayman Mossallam "Comparison of Failure Mechanisms in Composite Structure". SAMPE 2003 Conference Paper.



Failure Locations



Fracture Patterns



40 ft-lbf Impact Damage (Delamination) Predictions

Conclusions

- External damage visual indications DO NOT qualify the total damage extent
  - Specialized analyses required to determine damage state
- Currently no method exists to quantify residual strength
  - Many centers are working this solution
    - JSC, GRC, MSFC, KSC, others

Summary

- Visual indications do not represent the extent of structure damage
  - Delamination not obvious
  - Subsurface broken fibers
- COPV strength could be lower than the service pressure requirement

Quiz #5

Why is residual strength so important after the impact event?

A. So the COPV will fit into the system
B. It is a potential go/no-go factor
C. To preserve the ability to lift the COPV
D. To protect the COPV surface finish

Impact Control and Protection

Survey of Operations

COPV Program Industry Survey

- Manufacturing site visits (1993)
  - ARDE, Lincoln Composites, Structural Composites Inc.
- Spacecraft contractor site visits
  - Hughes Aircraft, Lockheed Martin (GE & LSOC, 1993)
  - NASA-AXAF Spacecraft at TRW (1997)
- Launch facility site survey (1993)
  - USAF launch facilities
    - CCAFS (DSCS & Titan)
  - NASA KSC launch facilities
    - VPF, HPF, OPF, VAB, Launch Complex 39B
- Impact damage workshop (1993)
  - WSTF survey

Survey Findings

- NDE methods
  - Visual, X-ray, UT, leak decay
  - Visual inspectors generally not trained to detect composite mechanical damage
- Manufacturing plants
  - Ensolite® foam protective covers, pads, supports
  - Compliant slings (GSE) for heavy COPV lifts
  - Wood and cardboard shipping containers
- Spacecraft contractors and launch facilities
  - Procedure for trained teams and observers
  - Tethered and inventoried tools
  - Ensolite® foam protective covers (limited hard-shells)
  - Use of impact indicators (Plexiglas covers)
  - Less procedural control as launch day approaches

Impact Control Plan

Impact Control Plan - Overview

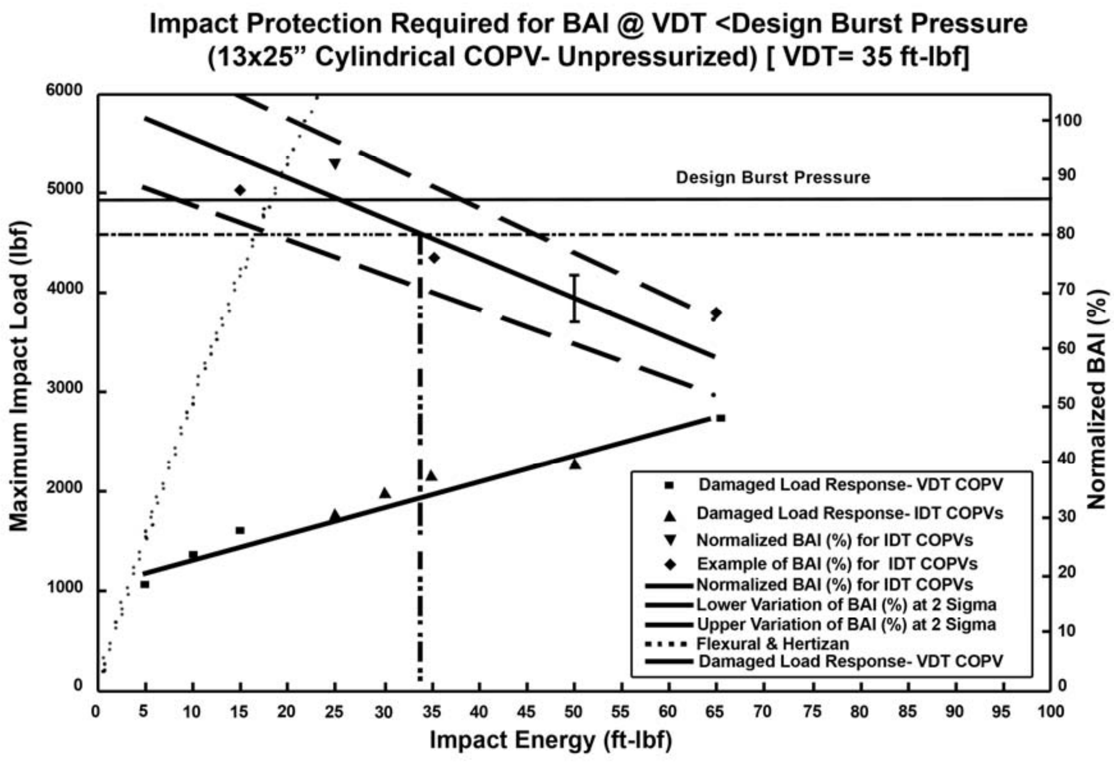
- Responsibility of the ***Prime Contractor***
- Must cover all stages of service live
- Ensures confidence that COPV will not fail due to mechanical damage from cradle to grave
- Particular attention required for pressurized work around

Mechanical Damage Control Requirements

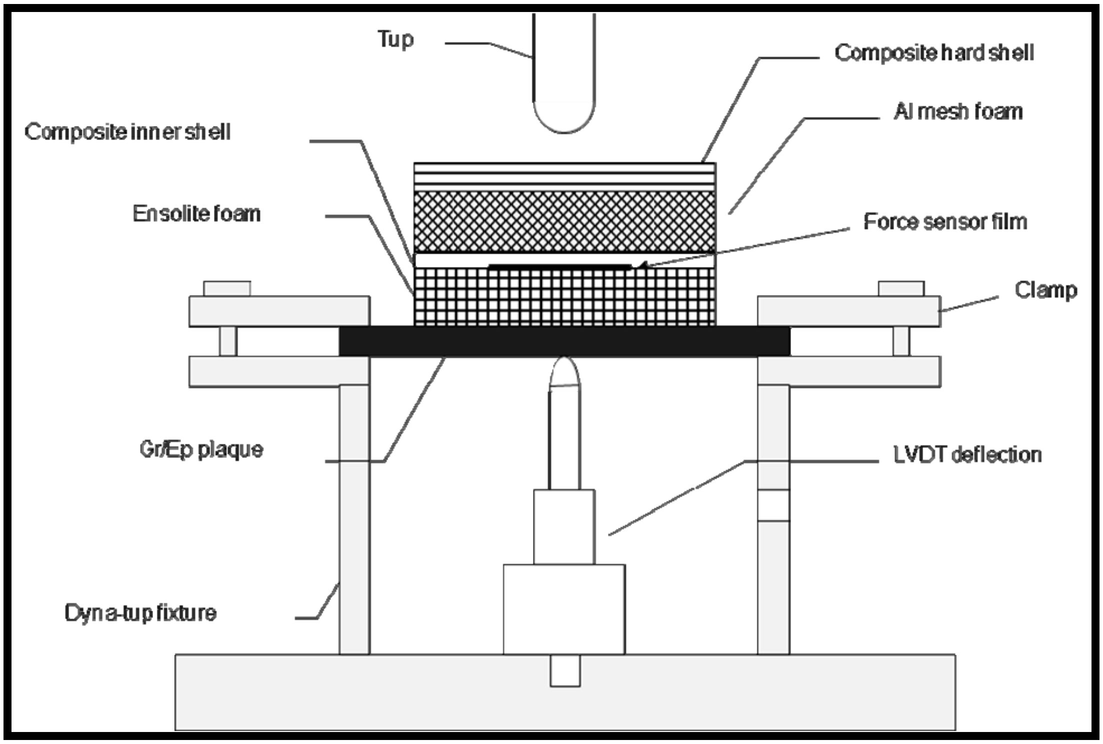
- ICP shall be created and contain
  - List of credible threats
  - Damage Mitigation plans/procedures and inspection points
  - Comprehensive operation, handling, and shipping procedures
- One or more of the following approaches shall be selected to satisfy that a damaged COPV will meet the minimum burst factor requirement
  - Protective Covers
  - Damage Indicators
  - Worst-Case Threat Damage Tolerance Testing
  - Visual Mechanical Damage Threshold Testing

Protective Covers

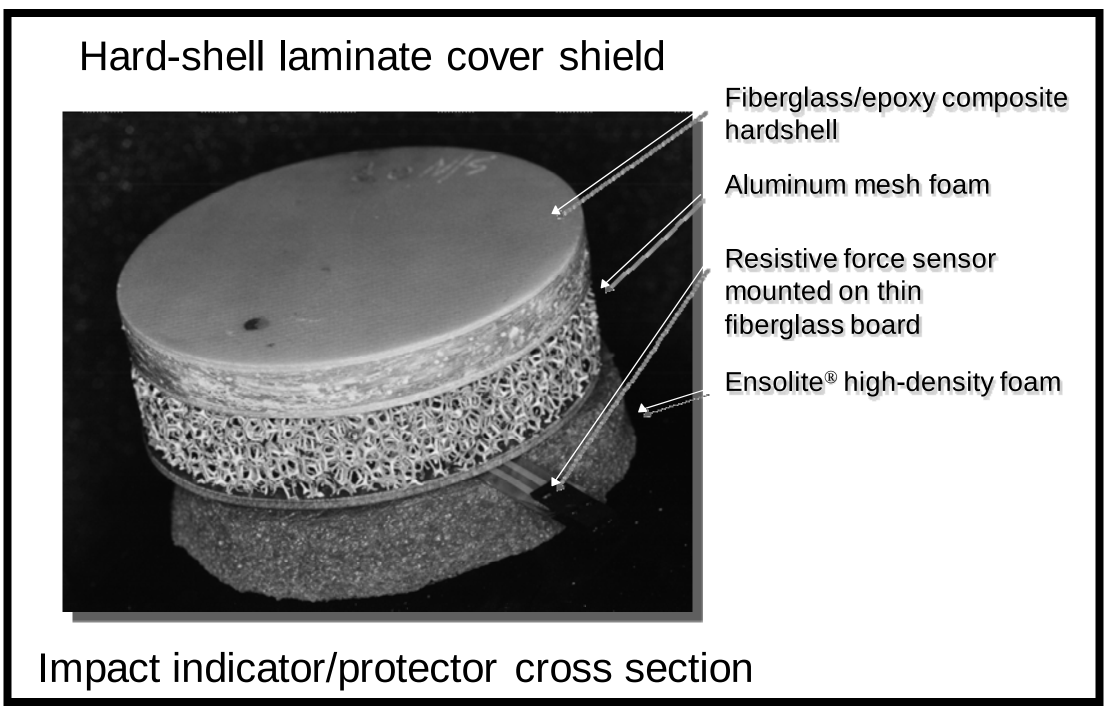
- Cover tested to demonstrate worst-case credible threat resulting in 5 ft-lb or less energy imparted to the COPV surface
- If energy is greater than 5 ft-lb the impact dedicated test article must be pressure tested to demonstrate the burst factor requirement is met.



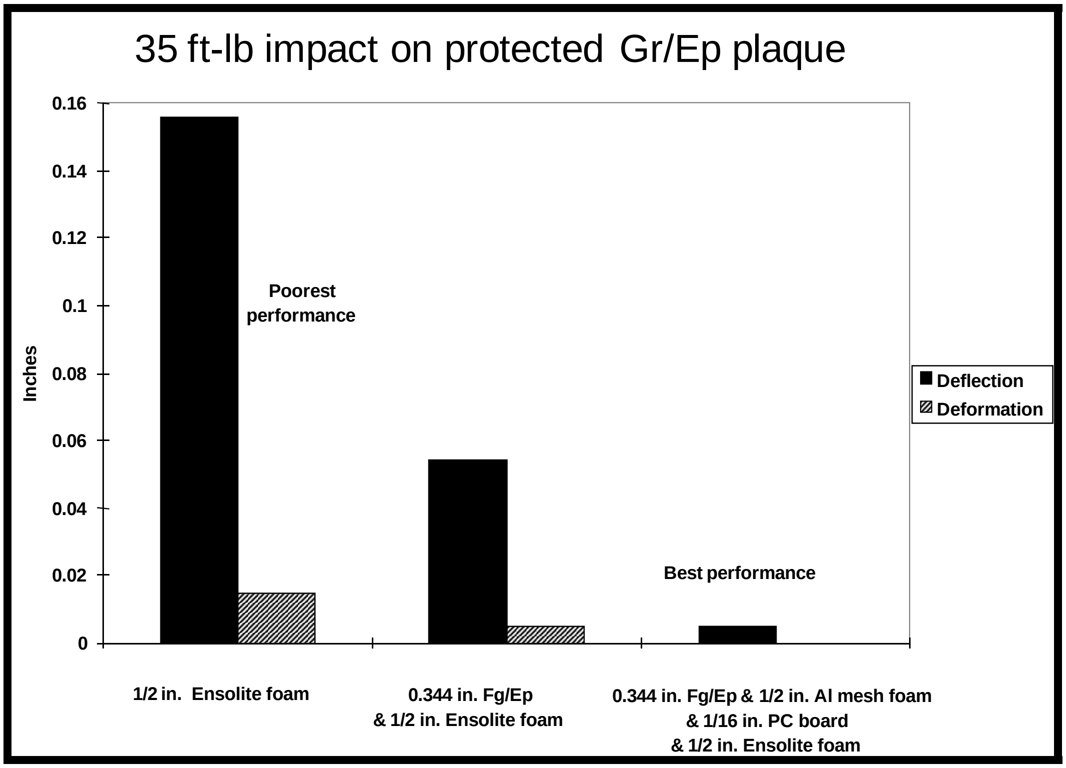
Procedure for CIE-VDT Testing



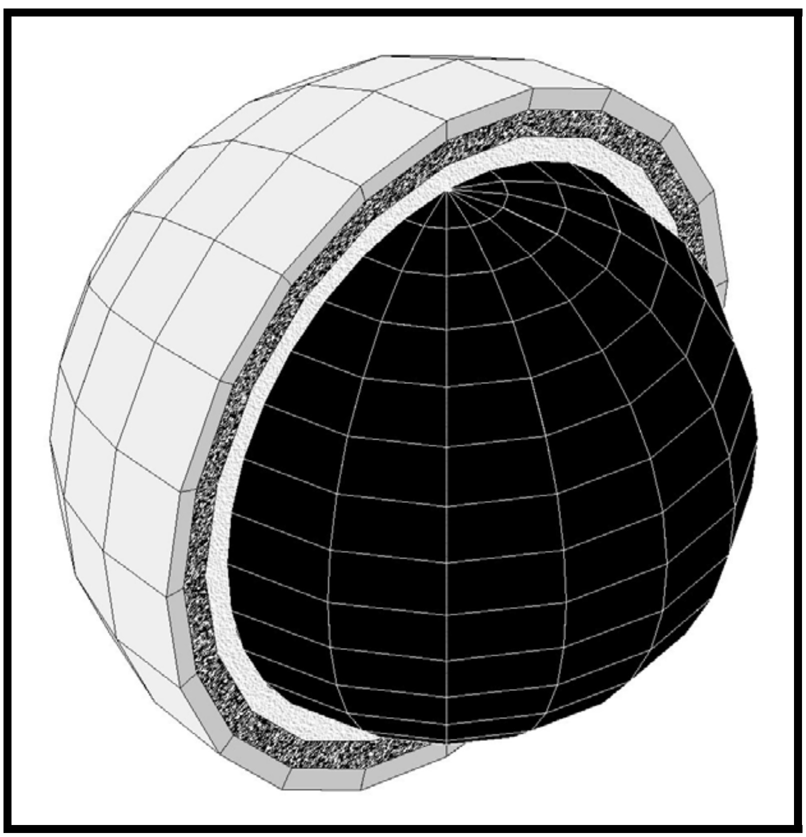
Indicator/Protector Test Fixture



Overview of Impact Protectors



Protector Mechanical Performance



Spherical Protective Cover

Damage Indicators

- Indicators tested to demonstrate sense of damage over range of 5 ft-lb to the maximum credible threat level
- If the minimum sensing energy is above 5 ft-lb, then a dedicated COPV must be impacted at that energy level and pressure tested to demonstrate the burst factor requirement is met

Note: 5 ft-lb correlated to impact data results

Impact Indicators

- Plexiglas/glass covers (foam-lined metal)
  - Provides protection for 5 ft-lbf impacts
  - Indicates COPV impact by failed cover
- Ensolite foam with force-sensing films
  - Provides protection for <1 ft-lbf impacts
  - Indicates COPV impact by electronic alarm
- Micro-spheres
  - Burst/break during impact event

Note: Must be able to manage false positives

Worst-Case Threat Damage Tolerance Testing

- Dedicated COPV may be tested to demonstrate it can with-stand 1.25X the worst-case damage and still meet the burst factor requirement.
- If this approach is used, no covers or indicator are needed.
  - Does NOT imply visual inspection points should not be identified (ICP)

Visual Mechanical Damage Threshold Testing

- Dedicated COPV may be tested to demonstrate that the damage energy creates visually detectable damage that will survive the pressure test and still meet the burst factor requirement.
- If this approach is used, the COPV must be visually inspected after the threat exposure and prior to pressurization
  - Visual inspection points predetermined in ICP

Credible Threats

- Depend on each stage of service life
  - Manufacturer
  - Shipping
  - Spacecraft/vehicle integrator
    - Installation and testing
    - Routine vessel service
- Inherent protective enclosures
  - Shipping container
  - Spacecraft/vehicle enclosure design
  - Flight service modules

ICP Documents Credible Impact Threats

Impact Damage Scenario	Weight (lb)	Impactor Description	Drop Height (ft)	Velocity (ft/s)	Energy (ft-lbf)	Pressurized COPV
Wrench swing impact	5-10	>1/4 inch hemispherical		5	4	Y, N
COPV swing in sling	>25	Edge or corner of equipment		3	4	N
Component installation	25-150	Edge or corner of component		2	10	Y, N
Crane hook impact	50-200	Crane hook		3	30	Y, N
Torque wrench slip	5-10	>1/4 inch hemispherical		15	35	Y, N
Scaffolding installation	100	Edge or corner		5	40	Y, N
Table height drop	5-25	Concrete floor	3		75	N
Hand tool drop	0-10	>1/4 inch hemispherical	10		<100	Y, N
Power tool drop	3-25	>1/4 inch hemispherical	10		<250	Y, N
45° stepladder tipover	80	Edge/corner of ladder impact	6		480	Y, N
Objects & tools drops	25-50	Tool box -- corner or edge	10		<500	Y, N
Rolling impact of forklift	6000	Breach of shipping container		3	850	N
Rolling impact of forklift	6000	Fork tongs, edge, or corner		3	850	Y, N

Impact Control Requirements - Keyed to design burst pressure

COPV Type	VDT (ft-lbf)	CIE (ft-lbf)	BAI_{VDT} (%)	Impact Control Requirements[a] (BAI_{VDT})
10.25 in. spherical	<5	35	74	Yes, ≤85%
19 in. spherical	<5	35	>93	No, >93%
6.6 x 20 cylindrical	<2.5	15	84	Yes, ≤84%
13 x 25 cylindrical	<5	35	80	Yes, ≤86%

[a]Impact indicators/protectors required if BAI_{VDT} is ≤ design burst pressure BAI value

NOTE: Any visible impact ≥ VDT requires MRB action for disposition

Quality Assurance Requirements

Quality Assurance Requirements

- Should be tied to the ICP
- Shall ensure no damage/degradation cradle-to-grave
- Defects which could cause failure are detected/evaluated and corrected

Inspection Plan

- Life of component cradle-to-grave
- Identify inspection points and techniques
- Accept/Reject standards shall be established for each point and technique

NOTE: Problematic for Composites

Inspection Techniques

- Selected NDE shall be performed prior to over-wrapping (radiography of liner)
- NDE detecting 90% probability at 95% confidence
  - Currently applies to metallic regions
- After winding/cure, visual inspection by trained inspector per ICP

Inspector Certification Program

- Trained COPV inspectors shall be utilized
  - Training
    - On-the Job Training (OJT) – manufacturer
    - WSTF Damage Detection Course
  - Recognized competent authority
- Expertise equivalent to ASNT or NAS 410
- Shall be specific to the composite/structure to be inspected
- COPVs/inspection techniques shall be identified in certification records
- Certification, re-certification, and individual shall be subject to approval from customer and/or AHJ

Acceptance Proof Test

- Every COPV shall be proof tested
- Temperature shall be consistent with critical use temperature
- Proof Pressure
  - P=((1+BF)/2)XMEOP for BF<2.0
  - P=(1.5XMEOP) for BF = or >2.0

Data Documentation

- Data shall be recorded/retained for the life of the COPV
- Data shall be reviewed periodically and assessed to evaluate trends/anomalies associated with related activities
- Results should be basis of any required corrective action

Precision Cleaning

Definition of Precision Cleanliness

- Clean rooms: Environmentally controlled areas for working on contamination sensitive hardware or assemblies
  - Class 10,000 or cleaner.
  - Many can meet Class 100 if proper care is taken
- Precision cleanliness shall be maintained to program requirements (e.g., JHG 5322 Level 200)

NOTE: JHG 5322 Level 200=No particles larger than 200 microns in a 100 milliliter sample of fluid from the system

- Non-volatile residue (NVR) level "A" standard is 1.0 mg/ft^2 with CFC 113 using 100 mL of fluid
- From Montreal Protocol CFC 113 has changed to HFE-7100 from compatibility test done at WSTF.
- Using the requirement of 0.3 mg/ft2 when using HFE-7100 is practiced at WSTF to achieve the same results as the old CFC standard due to the change in fluid NVR solvency.
- For solvent free systems Ultra Pure Water (UPW) and a Total Organic Carbon (TOC) machine can be used.

General Practices

- Solvents such as isopropyl alcohol (IPA), ACS reagent Low NVR grade or better, should be filtered to 10 microns or better prior to use (TT-I -735). Anhydrous is recommended.
- Precision cleaned hardware that has been welded shall remain properly bagged during the x-ray operations to avoid potential contamination
- Precision cleaned hardware cannot be exposed to an uncontrolled environment. This includes flow benches providing level 100,000 or better during inspections
- Hardware that must be transported outside the clean room must be bagged (often double-bagged).
- Clean room gloves are required when handling any precision cleaned flight hardware
- Insure gloves are approved for clean room use with low shedding properties
- Rinse gloves often with approve cleaner to limit cross contamination.
- Hardware that has not been precision cleaned shall not be brought into the vicinity of unprotected precision cleaned flight hardware
- Flight hardware must be wrapped in approved packaging material
- All precision cleaning fluid systems configured for flight shall have integrity seals installed

Sampling for Residual Solvent

- Liquids and residual particulate become trapped in crevices or absorbed into soft goods of assembled hardware. Achieving a accurate sample of assembled components is not obtainable and this practice is not recommended
- Some fluid systems are quite sensitive to these contaminants/solvents.

- ISS uses a 24-hour “lock up” to ensure gas sampling accurately reflects residual solvent concentration when required.

Ground Support Equipment

- Ground Support Equipment (GSE) that interfaces with precision cleaned flight fluid systems shall incorporate interface filters per SSP 30573
- These filters shall be located as close to the interface as possible
- Outlet lines require filters if it is determined that reverse flow could occur during the servicing or de-servicing operation
- GSE that interfaces with precision cleaned flight fluid systems shall be cleaned to at least the level of cleanliness of the flight hardware. Practice is that GSE is one level cleaner than the hardware being attached to insure attaching hardware is not contaminated from GSE.
- GSE fluid hardware, such as hoses and servicing units, shall be handled with, at least, the same cleanliness procedures as flight hardware

Tool Preparation

- Inspection tools (e.g., borescopes) that may be exposed to precision cleaned systems hardware shall be visibly cleaned and maintained clean
- Tools used in weld preparation and welding, such as cutters, weld heads and files, shall be visibly cleaned and maintained clean (e.g., bagged when not in use).
- Purge caps, mating QD’s and vent tools shall be precision cleaned to at least the level of the associated system and bagged after use

Purge Gas Practices

- Purge gas used during facing, welding, assembly, or disassembly shall meet the hydrocarbon and particulate controls per SSP 30573
- Purge gas used during facing, welding, assembly, or disassembly shall be supplied through precision cleaned low NVR/particulate tubing such as polyethylene, nylon, Teflon, or ethyl vinyl acetate

NOTE: Standard grade Tygon is not suitable

Maintenance of System Cleanliness

- All precision cleaned open tubes and lines must be protected (i.e., wrapped or bagged with approved materials) as soon as possible after fabrication. Purge gas used when possible
- Tubes and lines must remain wrapped until final installation
- Plastic Plugs touching the bare hardware is contaminating. Install plastic protective caps after proper bagging.

Oxygen Systems

- Regulators used during purging operations shall have O_2 compatible grease and cleaned to at least the level of the system being purged
- Purge tubing must be O_2 compatible

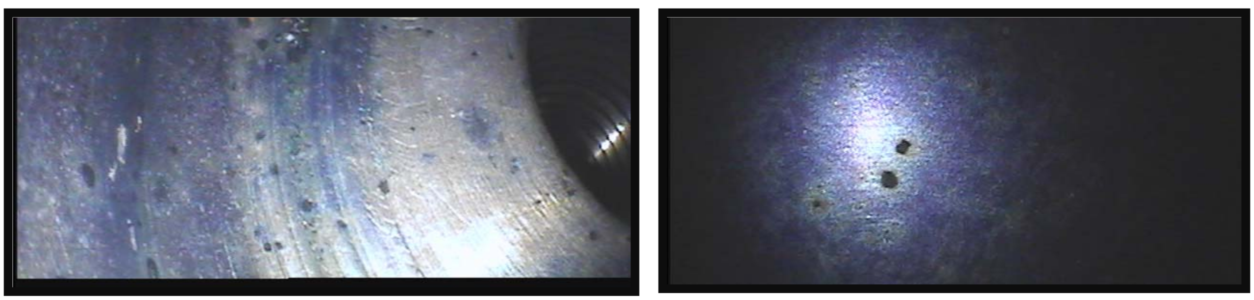
- Bagging materials used to store O_2 components shall be cleaned to the same level or better of cleanliness as the O_2 hardware, and must be O_2 compatible

Importance of COPV Cleanliness

- Prevent liner and weld corrosion
- Provide good bond interface between composite and overwrap
- Maintain cleanliness of interfacing system

Liner Contamination

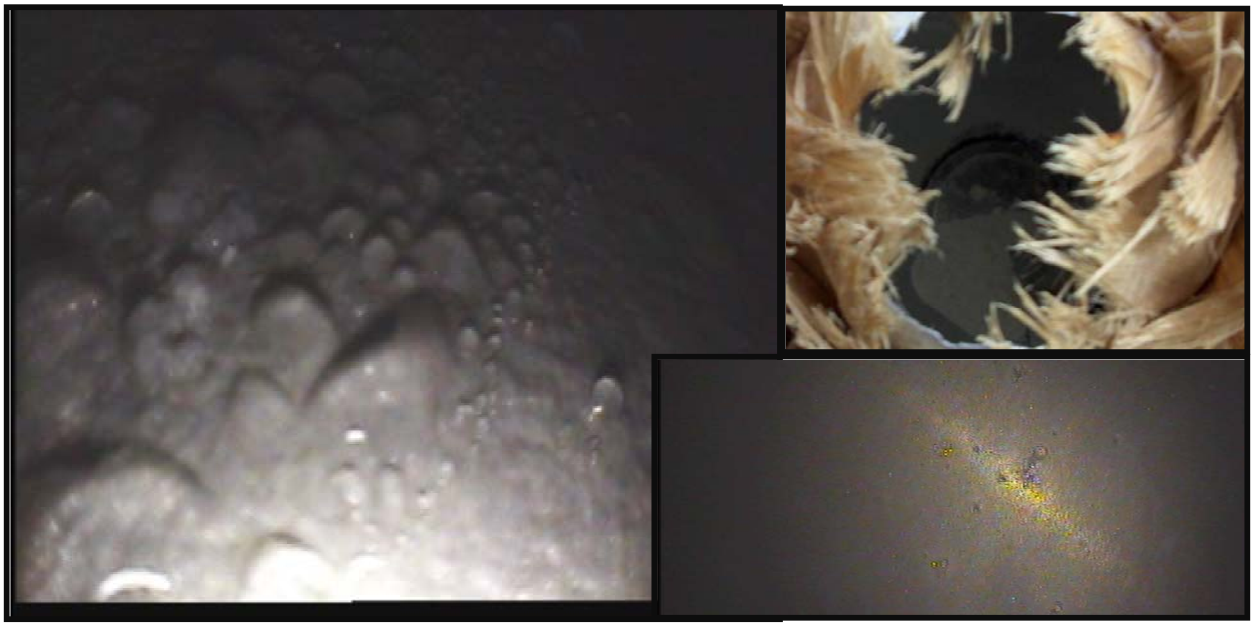
- 6AL-4V ELI Titanium Liner
- Liner bluing due to uncontrolled environment during heat treatment
- Pit corrosion due to vessel contamination during storage and use
- Vessel pad pressure with inert gas compromised
- Particulate in vessel above Level 100A requirement



Liner Contamination

Liner Corrosion

- Aluminum liner with water contamination at receiving
- Aluminum liner after sustained de-ionized water exposure



Liner Corrosion

Documentation

- JHG 5322, JSC Contamination Control Manual
- SSP 30573, Space Station Program Fluid Procurement and Use Control Specification
- SE-S-0073 National Space Transportation System, Fluid Procurement Specification
- MIL HDBK-407, Contamination Control Technology Precision Cleaning Methods and Procedures
- MIL HDBK-406, Contamination Control Technology Cleaning Materials for Precision Pre-Cleaning and Use in Clean Rooms and Cleaning Stations

Receiving and Periodic Inspection

Receiving Inspection

- Typically the first post-manufacturing inspection performed on a COPV
  - Compare to inspection performed by the manufacturer
- Start on the dock during component and/or subsystem receipt
- Should occur before accepting it from the manufacturer, contractor, or shipping company

- Ensures
  - Test article integrity
  - Conformity to spec for size & shape
  - Model and serial number verification
  - Verification of pressure connection and mounting structures

NOTE: 100% visual inspection of COPV interior and exterior surfaces (if possible)

What About X-ray?

- WSTF performed 100% X-ray on >150 COPVs
- Found minor occurrences of inclusions and porosity in weld
- None constituted a rejectable indication
- Simply provides a record of compliance

NOTE: Not typically of value

Periodic Inspections

- Must be tied to impact control plan
- Monitors for potential damage
- Performed from fabrication through launch and re-use (cradle to grave)

Periodic Inspection Schedule

- Performed at key manufacturing opportunities
  - Pre- and post-fabrication
  - Pre- and post-transportation
  - Prior to instrumentation application
  - Prior to integration
  - Before and after any pressure test
  - After operations involving heavy lift or heavy tools
  - Before close-out for launch
  - Prior to any re-use

COPV Program Inspections

- Inspectors examined 170 COPVs
  - Initially trained, monitored, and rotated
  - Conducted before and after impact, as well as during processing
- Assisted by corroborative NDE
  - Significant findings NDE assessed for possible reverification
- Some applications detect surface and subsurface damage undetectable by VT

Inspections Since COPV Program

- > 100 STEBs for Deep Space Program
- > 6 Flight STS Kevlar COPVs
- 7 Flight COPVs for CEV
- 100 Flight-Like COPVs for NNWG stress Rupture
- 4 NGV2 rated COPVs for AA-1
- 3 Flight COPVs for AMS-02
- 2 Repeats from COPV Program
- Numerous DOT rated and USAF Flight-rated COPVs

Quiz #6

Periodic inspection should occur

A. During pressure check-outs
B. Before and after system integration
C. After system close-out for launch
D. Once after post-manufacturing

Mechanical Damage Indications

Inconsistent Manufacturing Indications

- Cracks in resin or fiber
- Cuts, fiber breaks, and loose ends
- Scuffs, scratches, and abrasions
- Dents and dings
- Surface inclusions
- Surface discoloration
- Excess or lack of resin
- Other indications

Cracks

- Can be parallel or perpendicular to fiber
- Superficial – resin only
- Significant – fiber damage

Fiber: Cuts, Breaks, Terminations

- Longitudinal and transverse aspects
- Resin and/or fiber affected
- Tow termination
- Fiber parted – serious evidence of COPV damage requiring extensive investigation

Scuffs and Abrasions

- Directionality
  - Cross fiber
  - Along fiber
- Affected depth
  - Resin
  - Fiber
- Scuff related to mechanical impact
- Material transfer

Dents and Dings

- Indication that mechanical impact has occurred
- Anything visible is potentially significant
- Need be identified, located, and described
- Presence of delamination indicates impact
- All require corroborative NDE

Surface Inclusions

- Resin anomalies
  - Bubbles
  - Voids
  - Trapped fiber and debris

NOTE: Generally are artifacts of the manufacturing process

Surface Discoloration

- Discoloration is a VI finding
- Discoloration can be thermal, chemical, or mechanical
- Discoloration may be incurred during manufacturing and should have been noted
- Discoloration vs. crazing

Lean or Rich Resin

- Indicates poor process control
  - Excess resin can obscure vision
  - Burst bubbles can look like dents
  - Excess resin provides protection and weight
  - Lean resin makes fiber inspection much more subjective
    - Poor system performance
    - Reduced damage tolerance

Other Indications

Small Sphere, Abnormal Tie-off

4 x 9 in. Cylinder, Normal Tie-off

Typical Inlet Thread

Inlet Thread Damage

Visual Inspection Assisted by

- Training
  - DDC, OJT, AHJ accepted
- Written Procedures
  - ICP, WAD, Standard, other
- Appropriate Lighting
  - 50 candle-watt (minimum)
- Reporting Mechanism
  - MRB, inspection sheet, etc
- Inspection Kit
  - Magnification, mirrors, lights, coin

Written Procedures

- Inspections accomplished to written procedures
  - WSTF developed written procedures WJI-LFACMGMT-0006.B “Receiving and Handling Procedures for Composite Overwrapped Pressure Vessel (COPV) Test Articles/Hardware”
- Should be tied to or a part of ICP

Inspection Checklist Record

1.	Component Manufacturer:	
2.	Damage Control Plan:	
3.	Work Authorizing Documents:	
4.	Acceptance Data Package:	(NO) (YES) Location:________________
5.	Hardware Classification	Flight (CLASS 1) (CLASS 2) (CLASS 3) (NO) Proto-flight (YES) (NO) WSTF Critical (YES) (NO) Test Article (YES) (NO)
6.	Storage Requirements	None ( ) Controlled ( ) Bonded ( )
7.	Vessel Type:	(I) (II) (III) (IV) (V)
8.	Structure Geometry:	Width/Diameter:___________ (Sphere) Length:__________________ (Cylinder)
9.	Vessel Traceability:	Model Number:___________ Serial Number: ___________
10.	Materials of Construction:	Fiber Type:__________________ Resin Type:__________________ Liner Material:________________
11.	Visual Inspection Type:	(Internal) (External) (Both)
12.	Cleanliness Requirements:	(NA) (GC) (VC) (Other:_________)
13.	Mapping Convention:	Circumferential:___________ Latitudinal:_______________
14.	System Pressure:	(NO) (YES) ________________psi Media:_________________

Inspection Checklist Record		
15.	Hazardous Fluids (Fuels, Oxidizer, Asphyxiate)	(NO) (YES) List:________________
16.	PPE Requirements:	(NO) (YES) List:________________
17.	Safety Requirements:	NO) (YES) List:________________
18.	Special Training: Damage Detection Course (WSTF)	NO) (YES) List:________________
19.	Launch Site Pressure Test (1.1xMDP):	(YES) (NO)
20.	Photo Documentation:	(YES) (NO)
21.	Flash Photo Restriction:	(YES) (NO)
22.	Inventory Tools:	(YES) (NO)
23.	Tether Tools:	(YES) (NO)
24.	Inspection Records:	(YES) (NO)
25.	Composite Ply Lay-up documentation:	(YES) (NO)
26.	Reorient Structure/Craft:	(YES) (NO)
27.	Critical Lift:	(YES) (NO)
28.	Area Lighting (>50CW):	
29.	Structure Access: (Covers, insulation, structure, etc.)	
30.	General Note(s)	

Key VT Report Information

- Date
- COPV description
- VT observations
- Key observations
- Sketch
- Digital photo(s)
- Signature/stamp

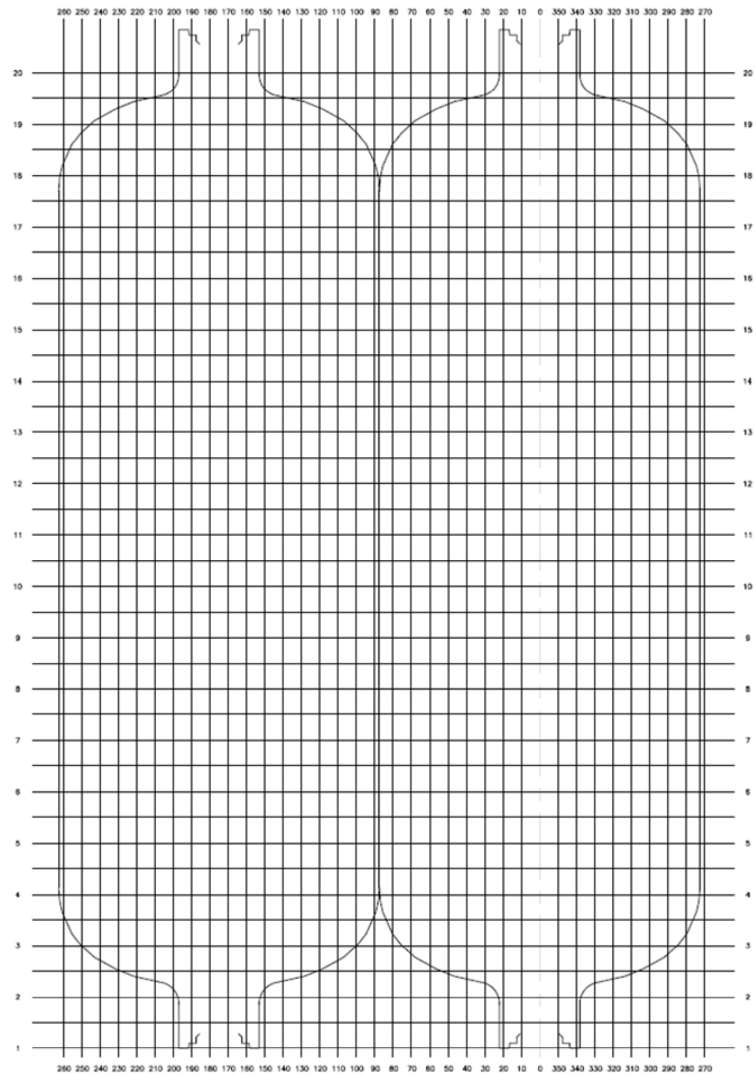
NASA/WSTF	P.O. Box 20 Las Cruces, NM 88012 (575) 524-5723
NTEC	

Manufacturer:	Serial Number:
Lot Number:	WSTF Number:
Vessel Geometry:	Dimensions:

Location	Description
Clocking: Lateral Measurements from:	
Notes:	

Inspector: ________________________ Date: ______________________

Sample WSTF VT Report



Notes:____
____
____
____
____
____

Manufacturer:__________ S/N:_________________ Inspector:__________________ Insp. Date:__________

Location of Indication

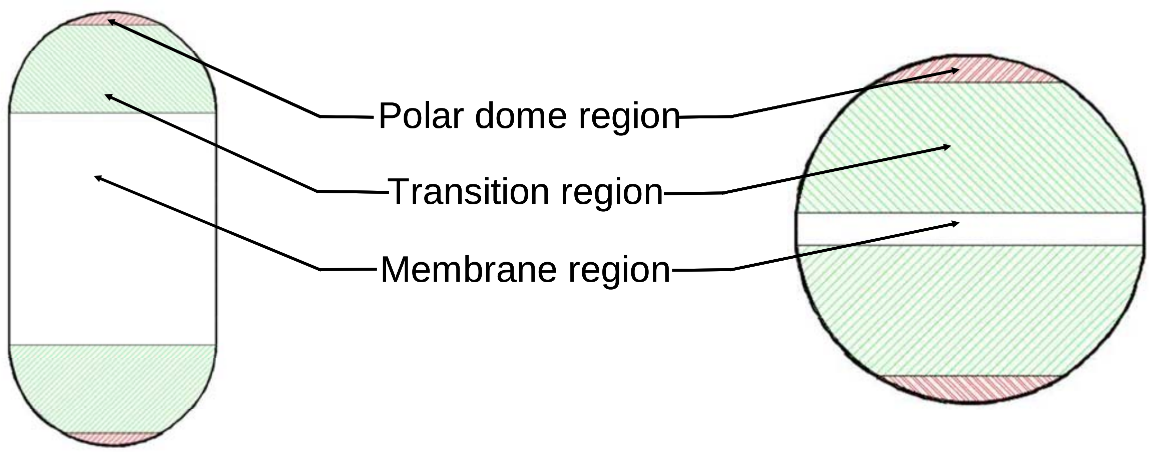
- Reference point must be identified and documented on inspection report
  - All measurements are taken from the documented common reference point
  - Must be clearly stated on inspection form
  - Boss is the typical latitudinal reference
  - Label is typical circumferential reference
  - May be scribed on boss by manufacturer
  - Review existing inspection reports

Damage Location

- All damage sites are documented from common reference point
  - Sites are circumferentially designated in degrees (0 to 360°).
  - Note clockwise verses counter-clockwise and orientation
  - All sites are measured down from the base of an identified boss
    - Differentiate between dual-ported COPVs

Importance of Proper Recordkeeping

- Map damage for future inspections
- Discuss findings without COPV present
- Clear record keeping precludes confusion
  - Large components
  - Multiple damage sites
- Quick identification of damage for MRB
- Pictures and sketches are invaluable



Damage Location Nomenclature

Impact Damage Indications

- Reported on form
- Discrepancy record initiated
- MRB action

Inspection Kit

Quiz #7

Damage inspection reports should note all of the following except

A. Location of the indication
B. Indication observation/description
C. Residual strength of component
D. Date and inspector

Inspection Techniques

COPV Program Nondestructive Evaluation

Objectives

- Develop Non-Destructive field inspection techniques
  - Demonstrate on flight-qualified COPVs
  - Characterize low-velocity impact damage
  - Investigate BAI correlation with NDE
  - Perform under multiple field-like conditions
  - Ensure applicability to field inspections
  - Assess qualitative vs. quantitative capability

Visual Observations

- Fiber Indications
  - Dents
  - Broken fibers
  - Cuts/scratches
- Matrix Indications
  - Cracking
  - Voids
  - Bubbles
  - Excess/lean resin
- Gross ply disorientations
- Other
  - Stray fibers
  - Water spots
  - Boss anomalies

NDE Techniques

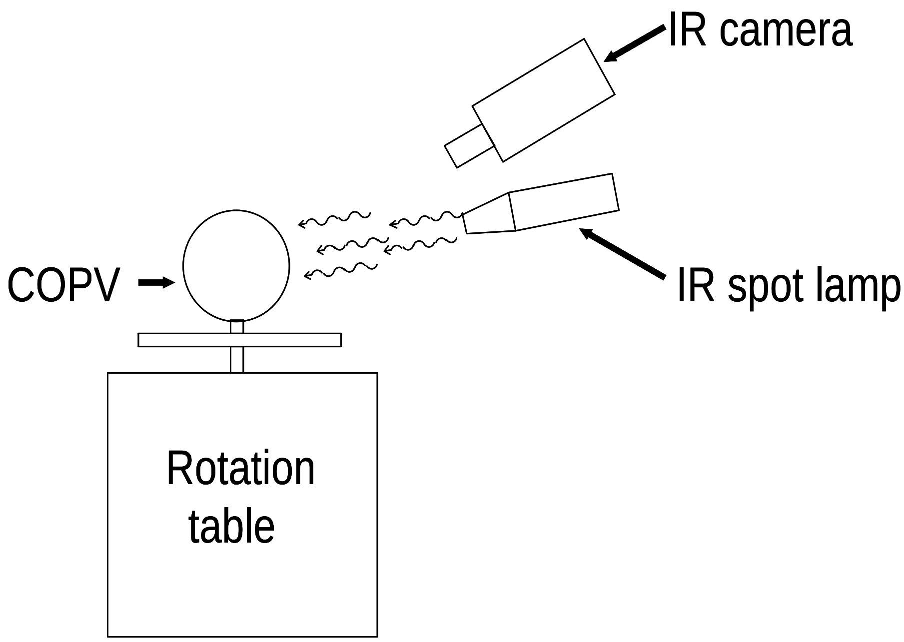
Acoustic Impedance Testing

- Complements visual inspection
  - Uses acoustic impedance to induce varying acoustic waves in composite structure
  - Inspectors learn to differentiate acoustic differences between damage versus undamaged regions
  - Detects subsurface liner deformations (buckles) and composite impact damage delaminations

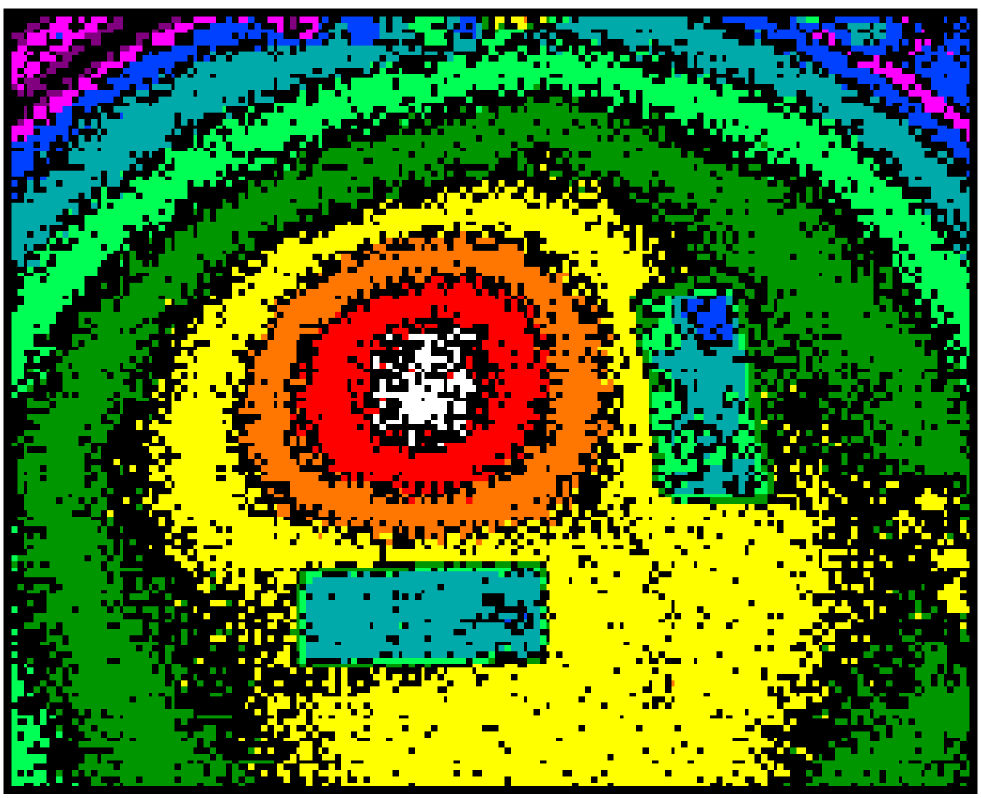
X-ray Radiography

- MIL-STD-453
  - Only identifies defects in metallic components
  - Typically requires five 72° angle views for large sphere
  - Overwrap tends to reduce sensitivity to metallic liner defects
  - Needs more development and standardization

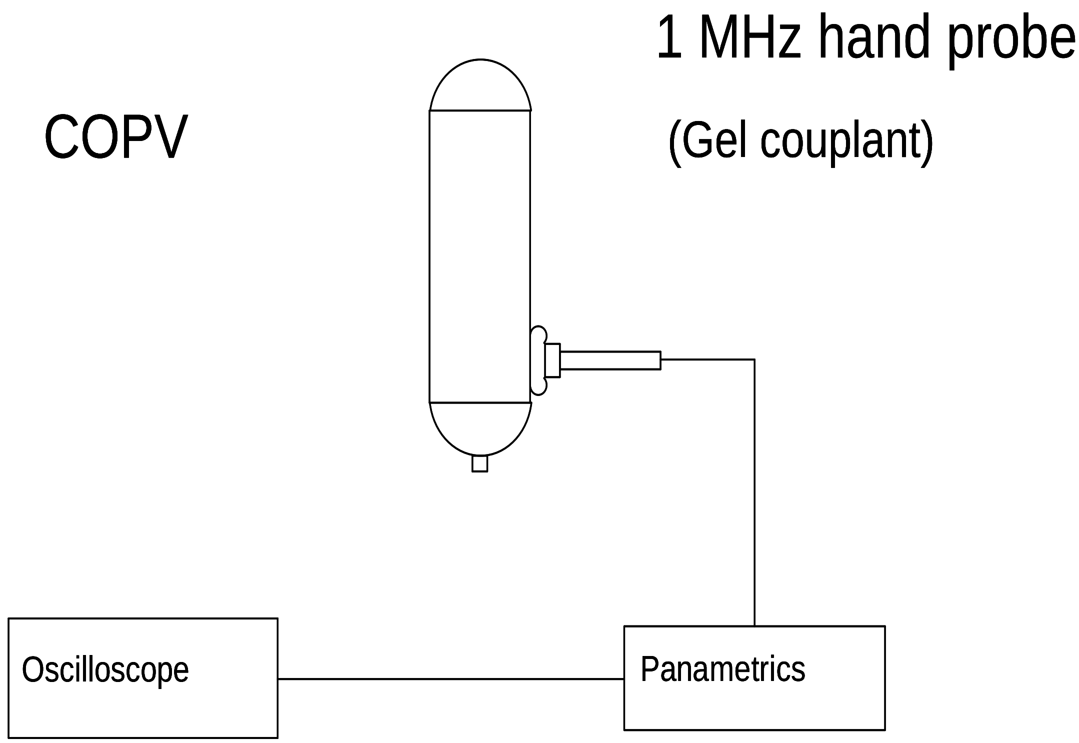
Typical X-ray Image



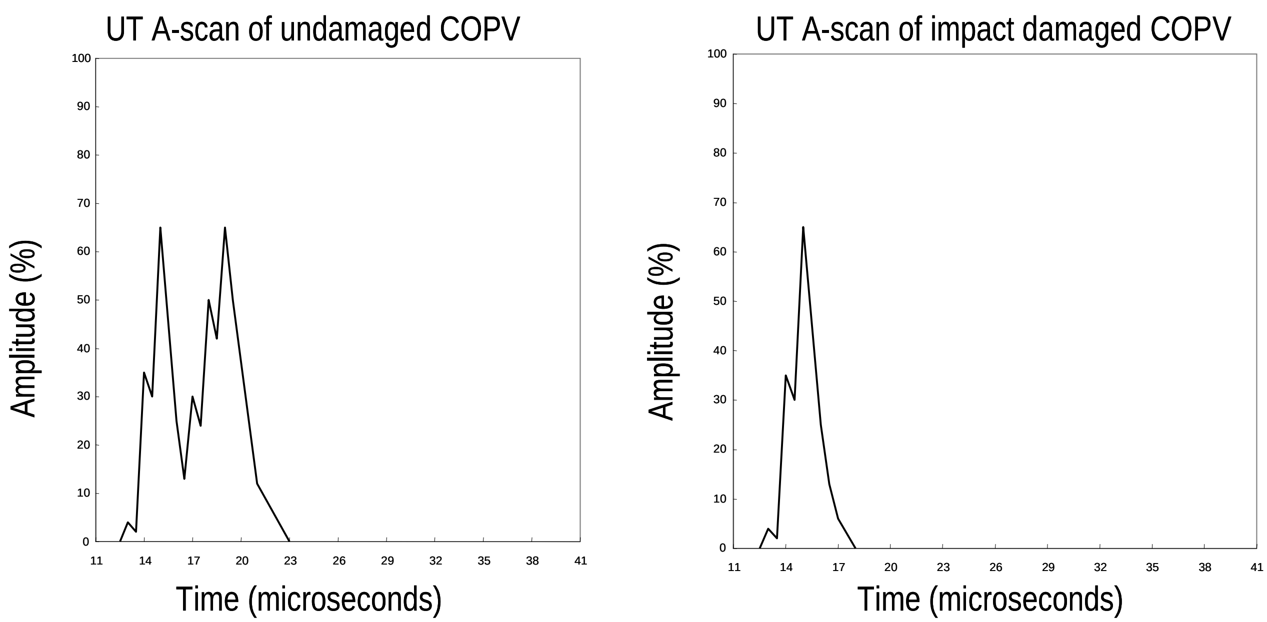
IR Thermographic NDE



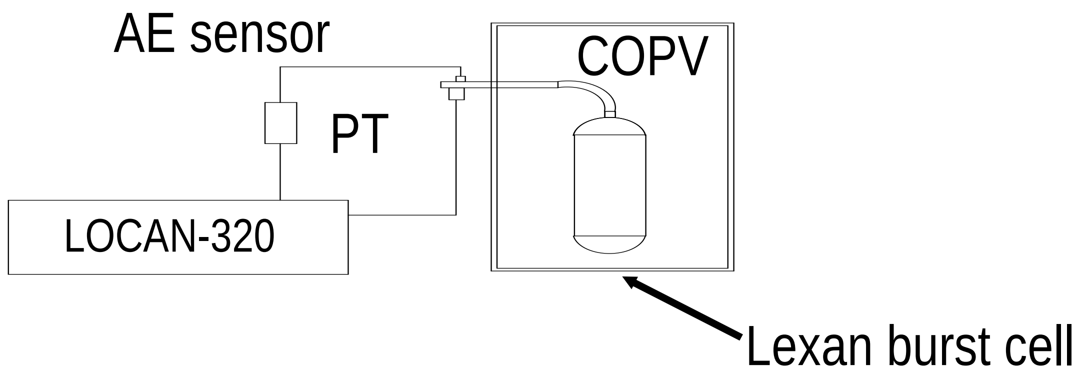
IR Thermographic Image - 35 ft-lbf impact on 10.25 in. dia spherical COPV



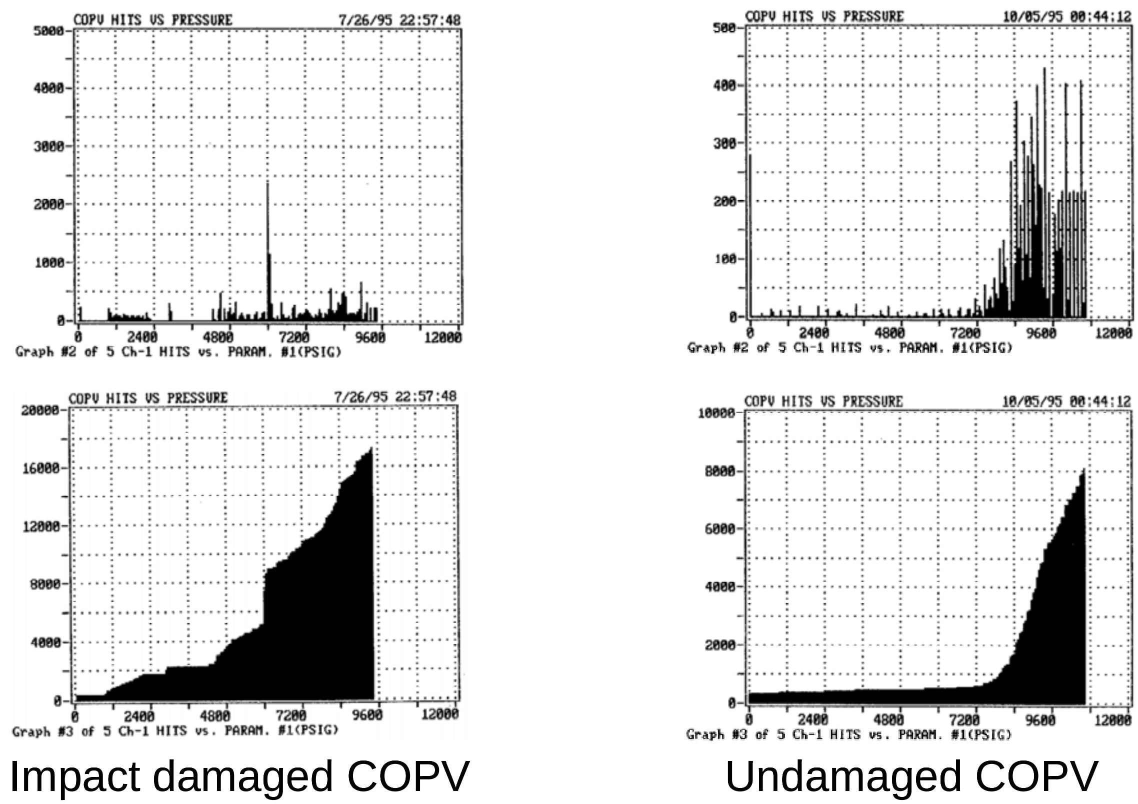
Ultrasonic A-scan NDE



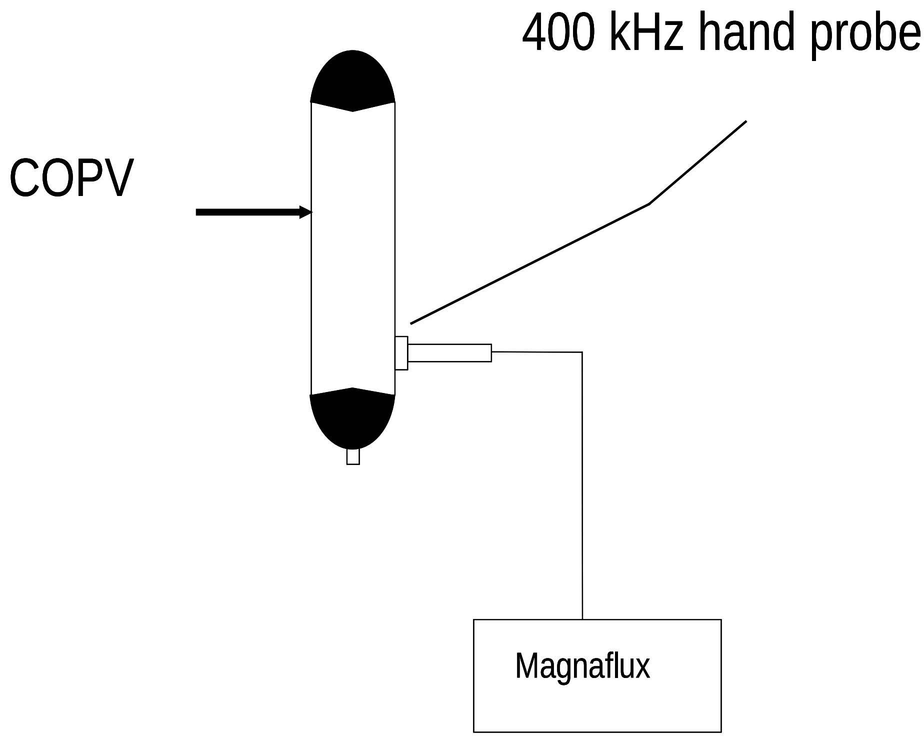
UT A-scan Profiles



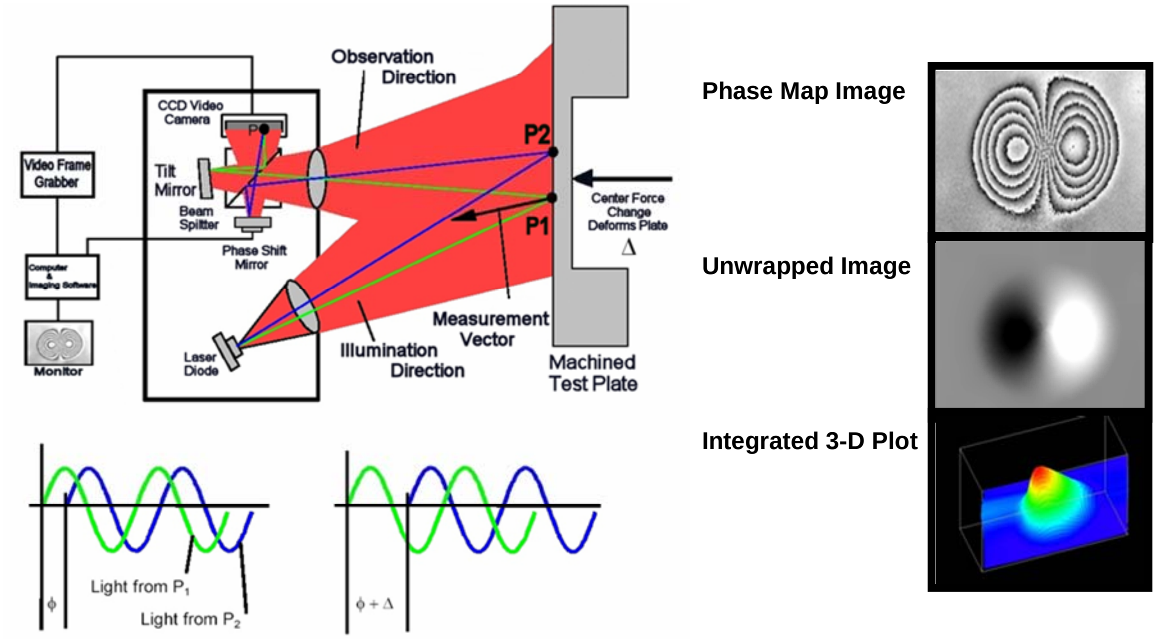
Acoustic Emission NDE



Acoustic Emission Spectra

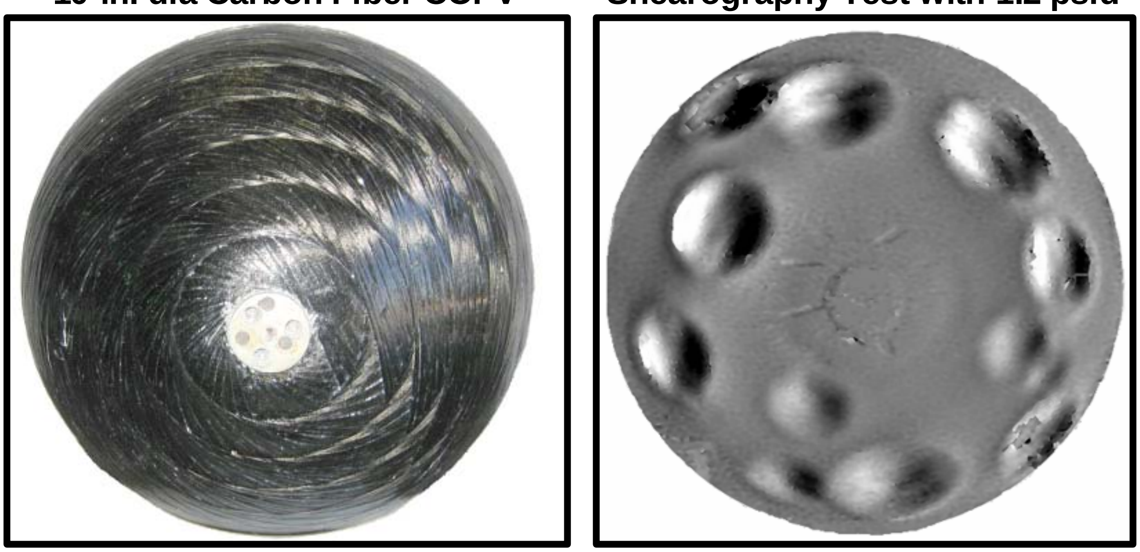


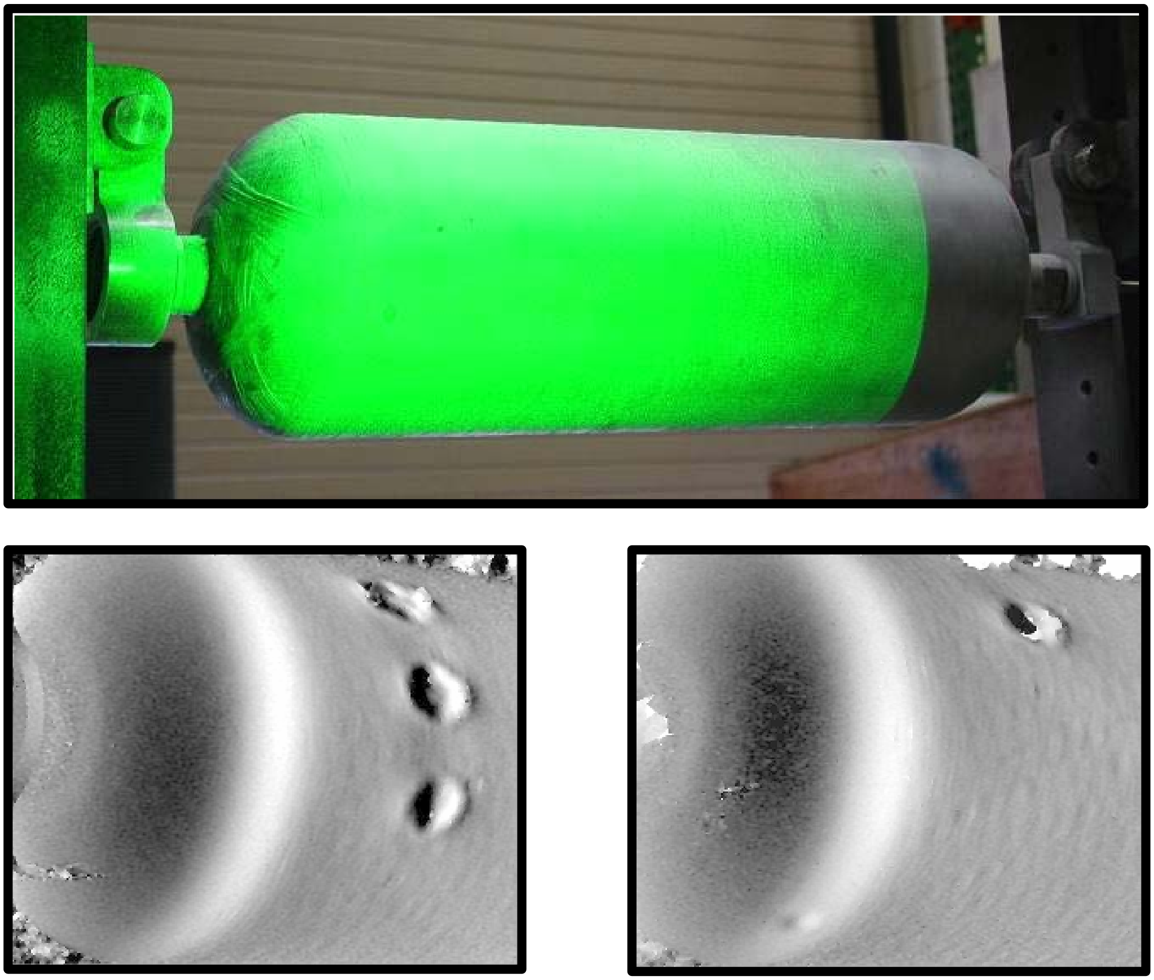
Eddy Current NDE



Post-Program NDE Laser Shearography

10-in. dia Carbon Fiber COPV **Shearography Test with 1.2 psid**

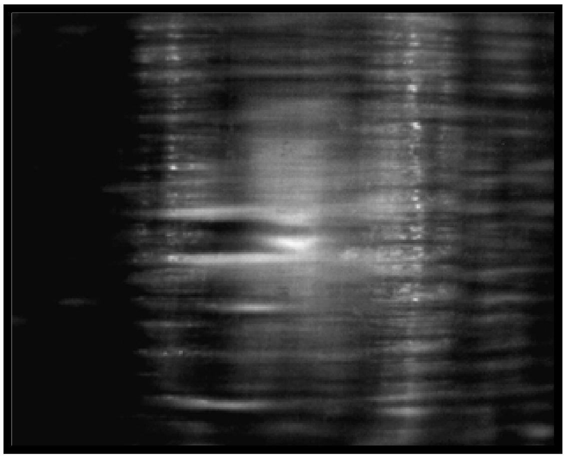




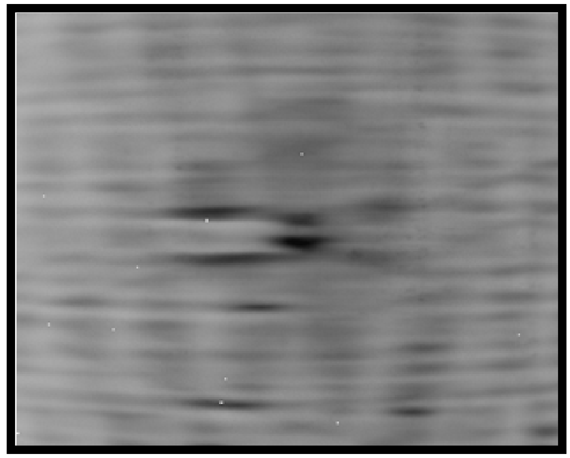
Program COPVs

Flash Thermography

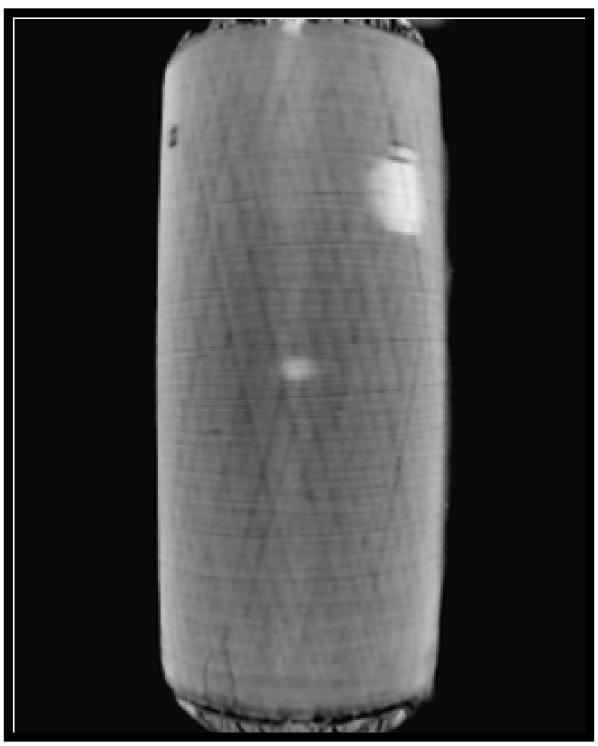
- Principal Components Analysis (PCA) allows numerical processing of hundreds of images to simplify dataset and highlight details not seen from single images

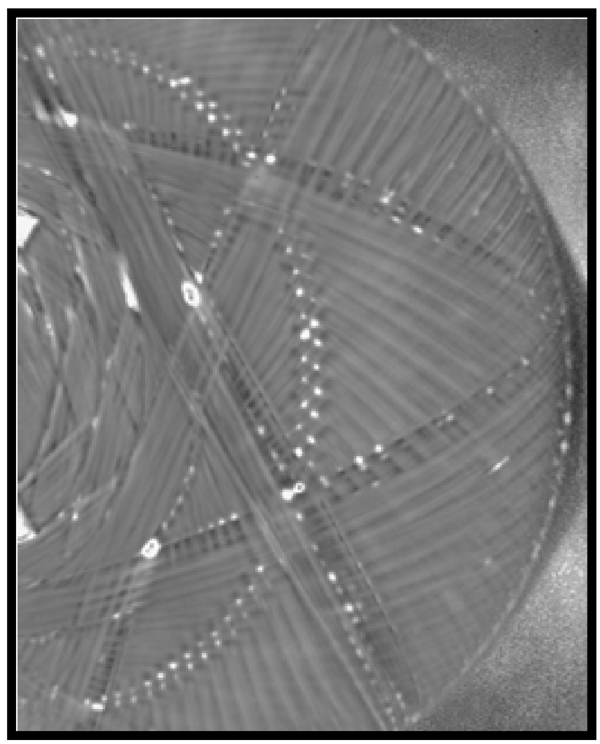


Circular impact site at center w/ delamination, damaged tow, and subsurface spreading around impact



Damaged tow w/subsurface delamination shown as darker regions above and below impact site





Quiz #8

Which NDE technique is best for determining broken fibers on the surface?

A. IR thermography
B. Ultrasonic testing
C. X-ray
D. Visual inspection

Application of Techniques

Recommended Methods of COPV NDE Indications

- Qualitative
  - Visual: Global inspections and local diagnostics
  - IR Thermography: Global inspections and local diagnostics
  - Acoustic Emission: Possible global/local monitoring technique
  - Eddy current: Local diagnostics
  - Ultrasonic: Local diagnostics
  - Acoustic impedance: Local diagnostics

NOTE: The use of multiple NDE methods improve detection ability

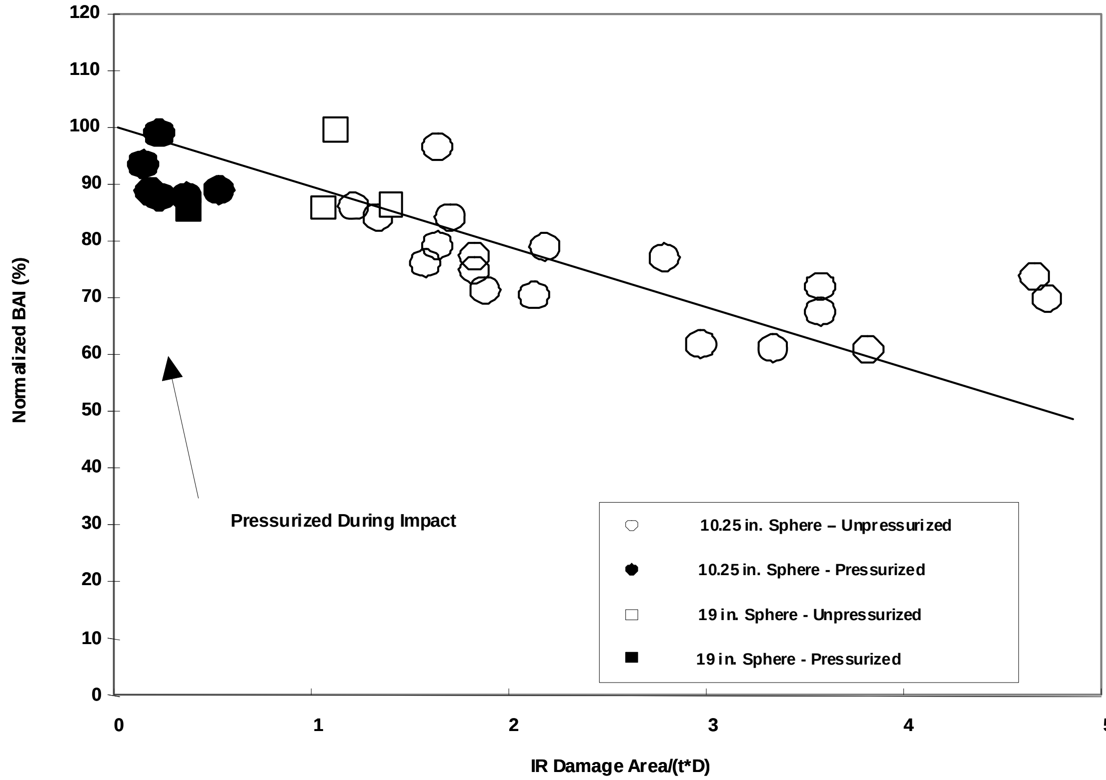
NDE Application Matrix

TYPE OF DAMAGE	TYPE OF NDE INSPECTION							
	Visual	Acoustic Impedance	Radiograph	Ultrasound	Heat soak Thermography	Eddy Current	Flash Thermography	Shearography
Indentation	●	◎	◎			◎		◎
Chip (Fiber Damage)	●	◎		◎	●		●	●
Crack (Fiber Damage)	●				◎		◎	●
Scratch (Fiber Damage)	●				◎		◎	●
Scuff (Fiber Damage)	●	◎		◎	●		●	●
Void (Internal)		◎	◎	●	●		●	●
Delamination		●		●			●	●
Liner Disbond		●		●	●		●	●
Liner Defects	●		●		◎	◎	◎	◎
General Diagnostics	●	●	●	◎	●		●	●
Local Diagnostics	●	●		●	●	◎	●	●

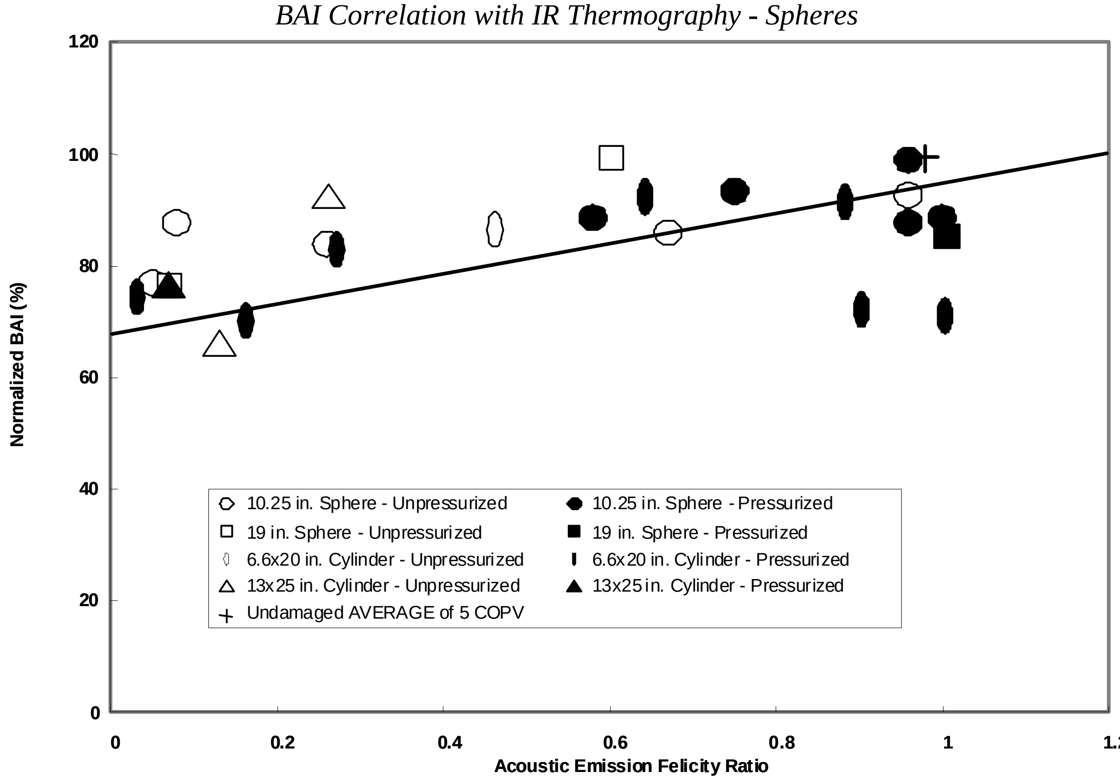
● **Recommended method**

◎ **Limited Usefulness**

- Quantitative
  - Large data scatter in residual burst strength after impact
  - Precludes accurate prediction of burst strength from qualitative NDE data



BAI Correlation with IR Thermography - Spheres



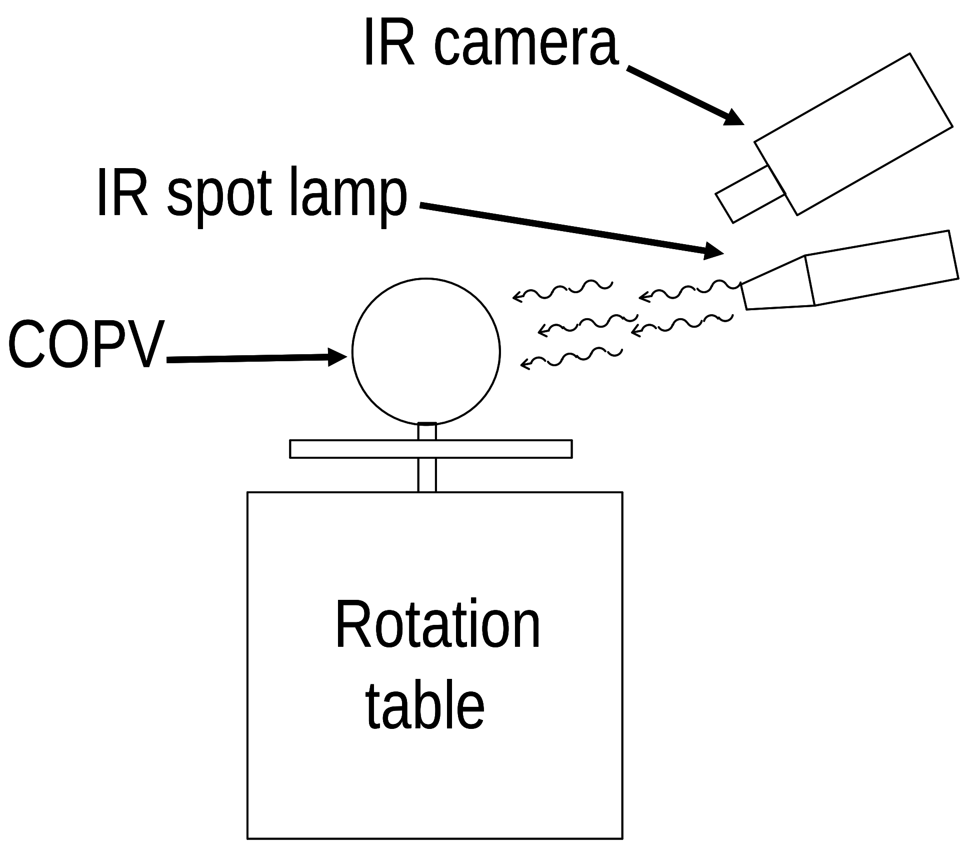
BAI Correlation with AE

Demonstration of Techniques

Acoustic Impedance Technique

- Select signal generator
  - May require coin without ridges
- Choose quiet environment
- Develop a “rhythm” to induce monotonic taps
- Audible frequency and amplitude results between undamaged and damage regions.

NOTE: This change in response indicates potential liner deformation or composite delamination.



IR Thermographic NDE

Equipment Selection

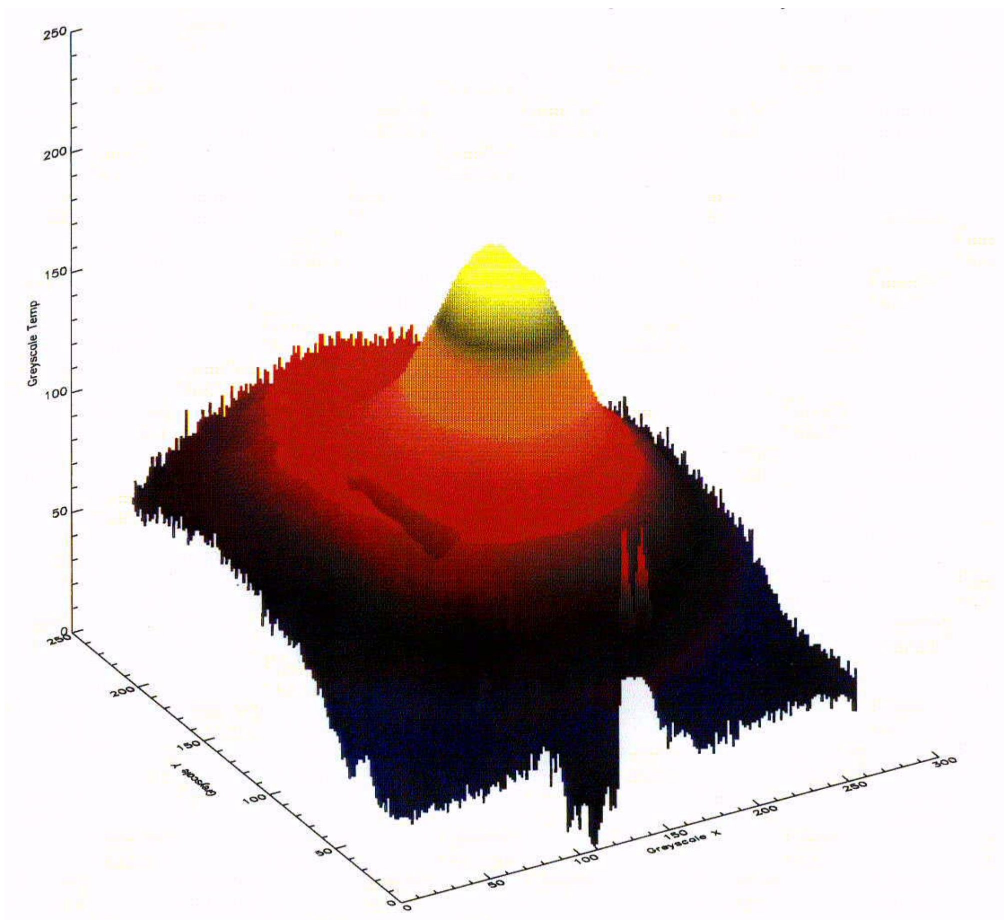
- IR camera
- Quartz lamp
- COPV fixture table
- Other equipment
  - Meter rule
  - Reflective tape

IR Thermography - Diagnostic Inspection

- Position and zoom to suspect region
- Place quartz lamp ~ 30 to 50 cm from and 30° relative to camera line of sight
- Heat large area of COPV to drive IR image just above saturation level for 5 to 10° C range
- Extinguish lamp and capture images
- Keep temperature from exceeding rated limit
- Identify hot spots in video playback
- Measure hot spots areas against reflective tape areas
- Correlate with other NDE indications

IR Thermographic Image

Video of IR Thermographic Image (35 ft-lbf impact on small sphere)



Visual Inspection and Surface Photos

Visual Inspection Photos

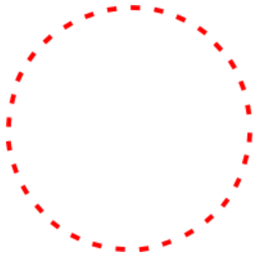
- Represent characteristic damage observed in COPV program
- Can be used for damage comparison
- Documents:
  - Impact and surface damage
  - Normal manufacturing indications

NOTE: Must understand the difference

Impact Condition Legend

- COPV characteristics
  - Size, shape
- Impact conditions
  - Impact energy, tup size, and shape
- Pressure conditions
  - Media and pressure

LEGEND

	**ESTIMATED IMPACT LOCATION**
I A	**IMPACT AREA**
CFR	**CUT AND/OR CRUSHED FIBERS**
BF	**BROKEN FIBERS**
	**IMPACT LOCATION ON COPV**
L	**LONGITUDINAL CRACK**
T	**TRANSVERSE CRACK**
TE	**TOW EDGE**
F 	**FIBER WIND DIRECTION**
~ 3X	**MAGNIFICATION (Approximate)**

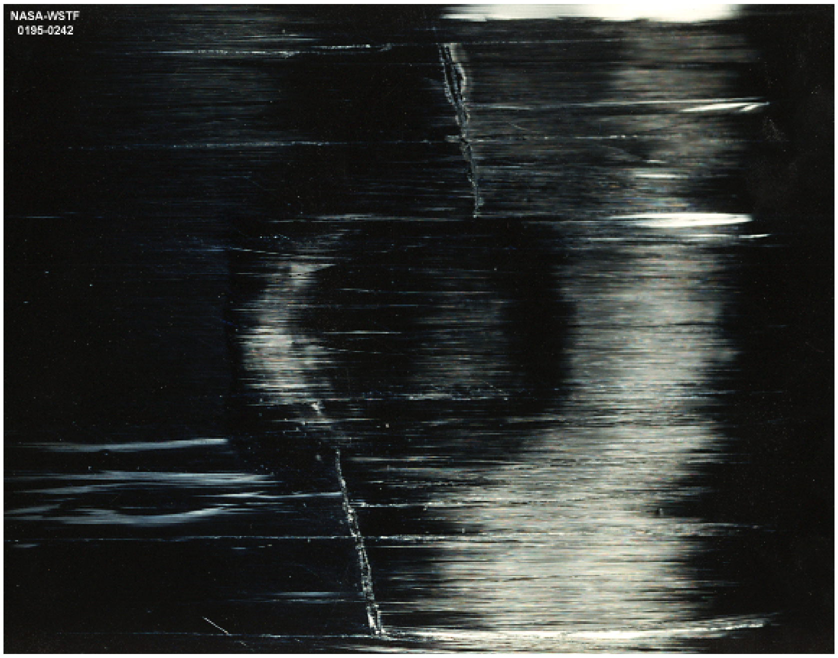
Surface Indications

- Special impacts
- Cracks
- Scratches
- Cuts
- Abrasions
- Fiber and resin anomalies
- Thread damage

Damage Examples

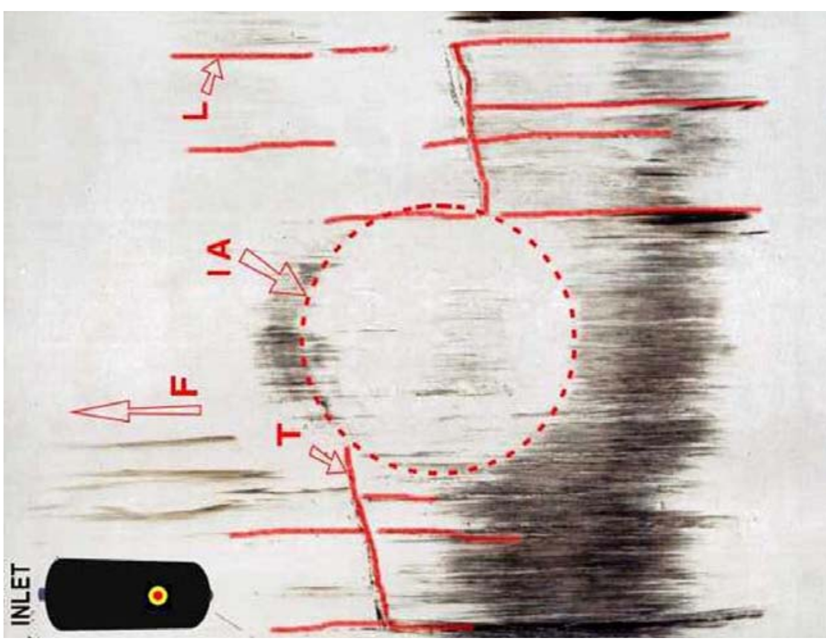
- 6.6 x 20 in. cylinders
- 10.25 in. dia spheres
- 13 x 25 in. cylinders
- 19 in. dia spheres
- 6.6 x 20 in. cylinder, oblique
- Visual inspection photos

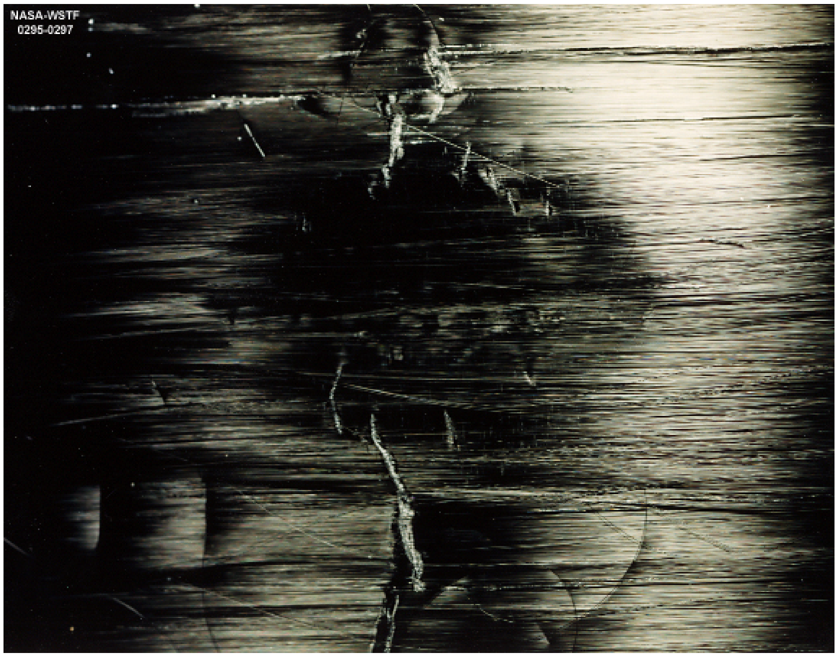
6.6 x 20 in. Cylinders



Small Cylinder, Unpressurized, 5 ft-lb Impact, 0.5 in. Tup

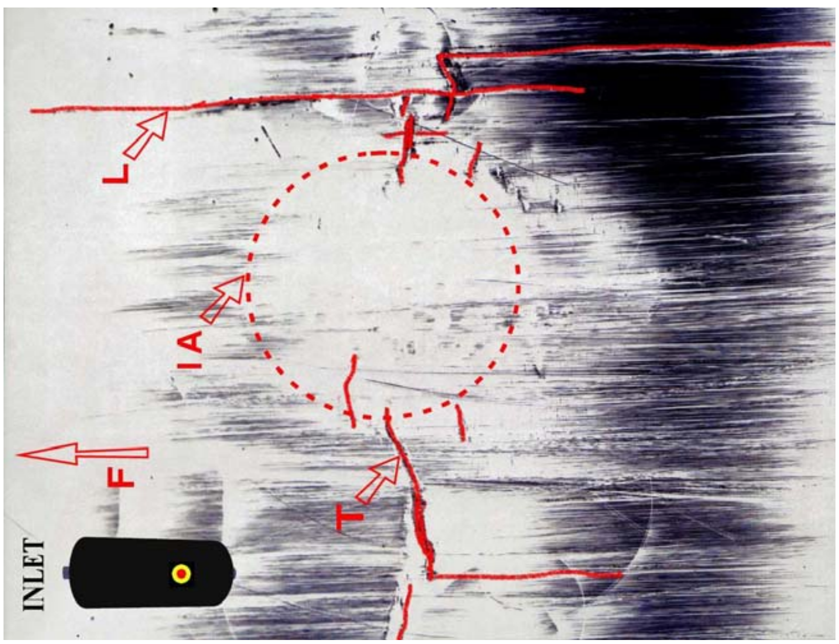
A low-energy impact to an unpressurized cylindrical COPV in the hoop region usually results in a shallow indentation. Note the transverse cracks emanating from the indentation edges and joining/ending at the longitudinal cracks parallel to the fiber winding direction. Typically there are no significant transverse cracks in the indentation itself at this energy level. This type of impact damage is near the visible threshold and is easily overlooked.





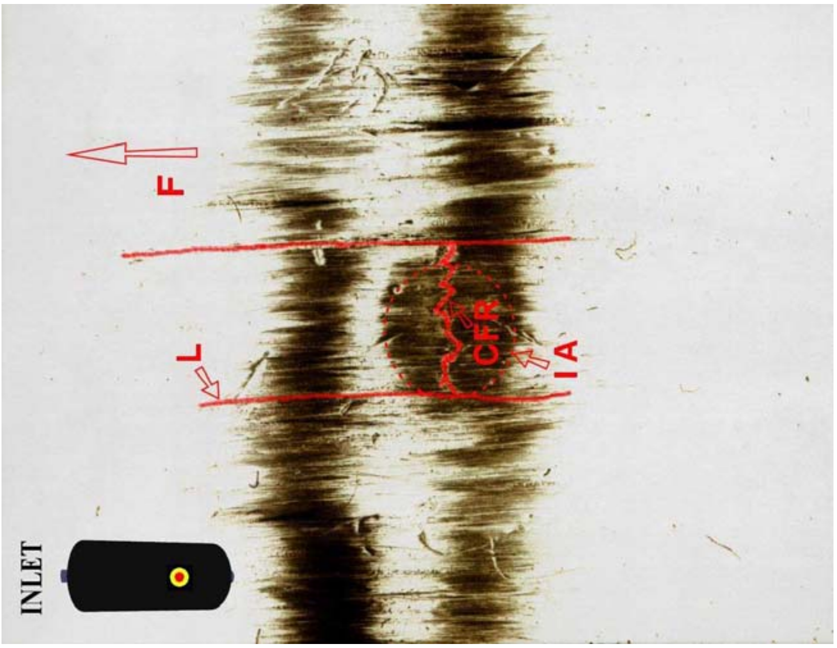
Small Cylinder, Unpressurized, 15 ft-lb Impact, 0.5 in. Tup

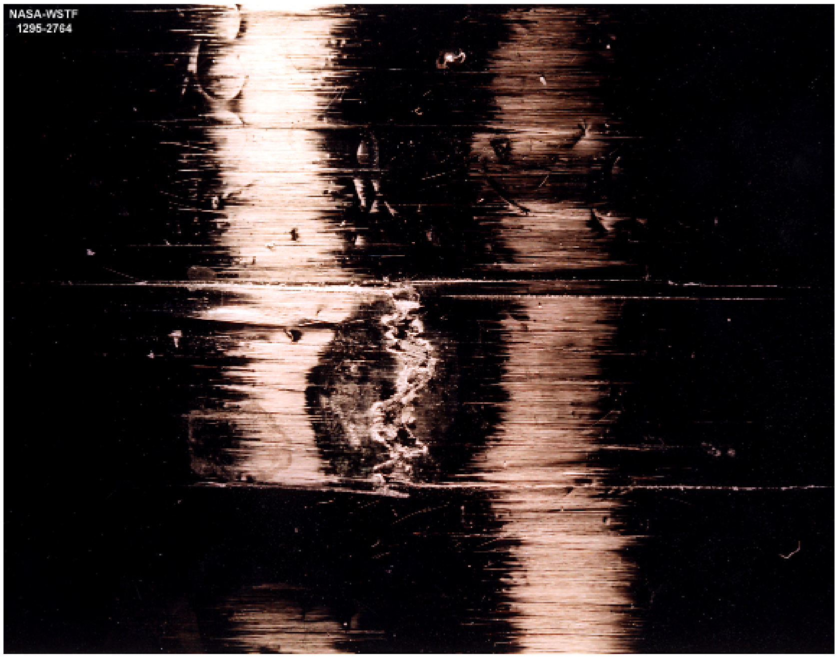
This is very similar to the previous example, except minor transverse cracking is now seen in the indentation. This was impacted at the damage threshold level.



Small Cylinder, 6000 psi Hydraulic, 15 ft-lb Impact, 0.5 in. Tup

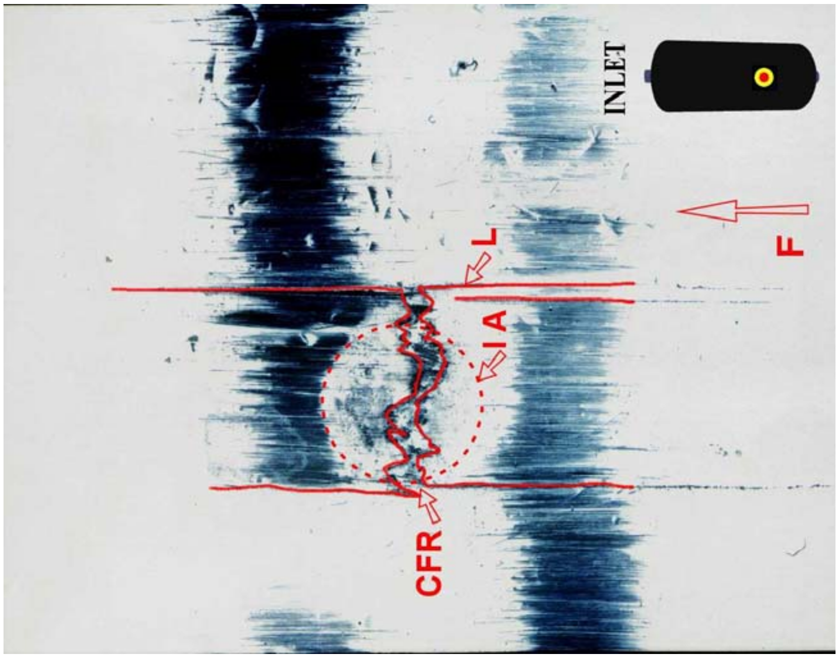
An impact to a hydraulically pressurized to MEOP cylindrical COPV in the hoop region usually results in a very shallow indentation. Note the continuous transverse crack bisecting the indentation and joining/ending at longitudinal cracks parallel to the winding direction. Trans-impact site cracking is a prominent feature of this type of impact damage and can result in fiber delamination. 15 ft-lb is the designated damage threshold level for this type of COPV.





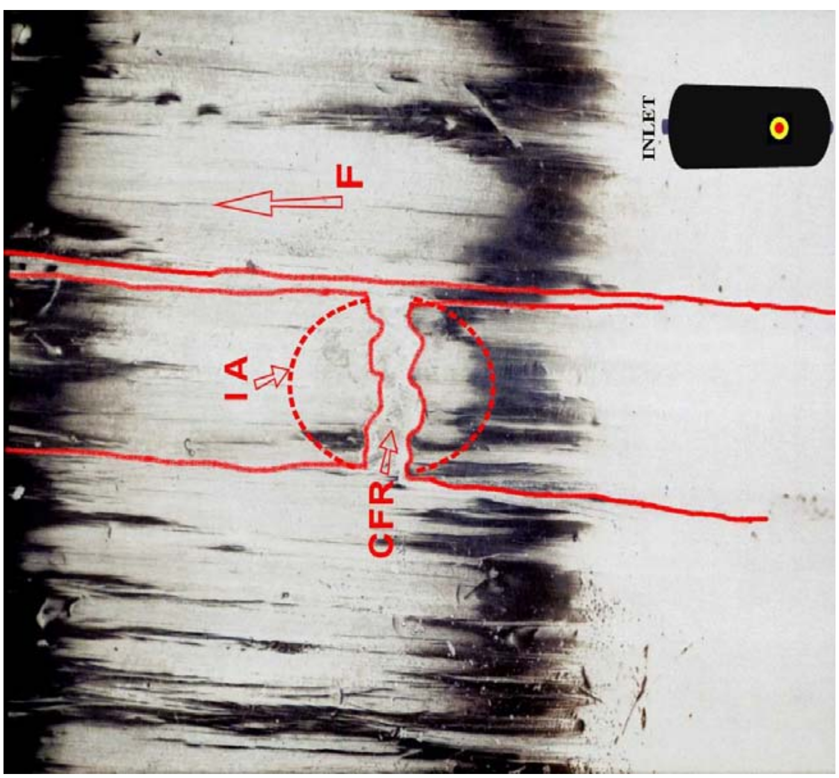
Small Cylinder, 6300 psi Pneumatic, 15 ft-lb Impact, 0.5 in. Tup

An impact to a pneumatically pressurized to MEOP cylindrical COPV in the hoop region usually results in a clearly visible indentation. Transverse damage site cracking and fiber low delamination are characteristic and more highly visible than the hydraulic case.



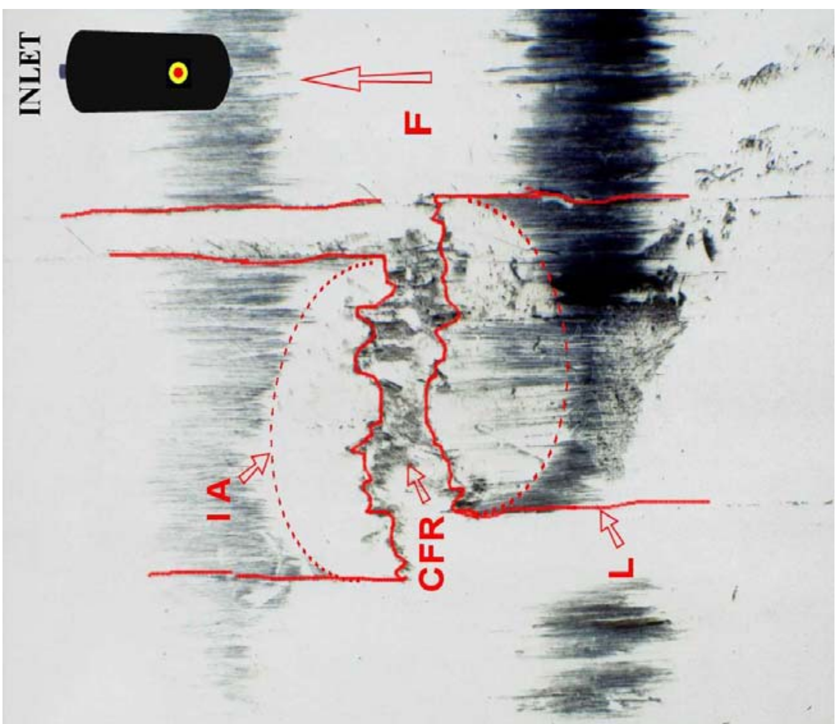
Small Cylinder, 6000 psi Hydraulic, 15 ft-lb Impact, 0.5 in. Tup

Another example of the same type of impact conditions as previous. Note the more highly visible transverse impact site cracking, separation and delamination. This impact resulted in a 31.1 percent degradation of strength with the resulting burst occurring just below the proof pressure level (7500 psig) for this type of COPV.



Small Cylinder, 6300 psi Pneumatic, 15 ft-lb Impact, 0.5 in. Tup

Another example of the same type of impact conditions as in a previous example. Here indentation, transverse damage site cracking, and delamination are more evident. This example indicates pneumatic damage is more visible than the hydraulic or unpressurized cases.



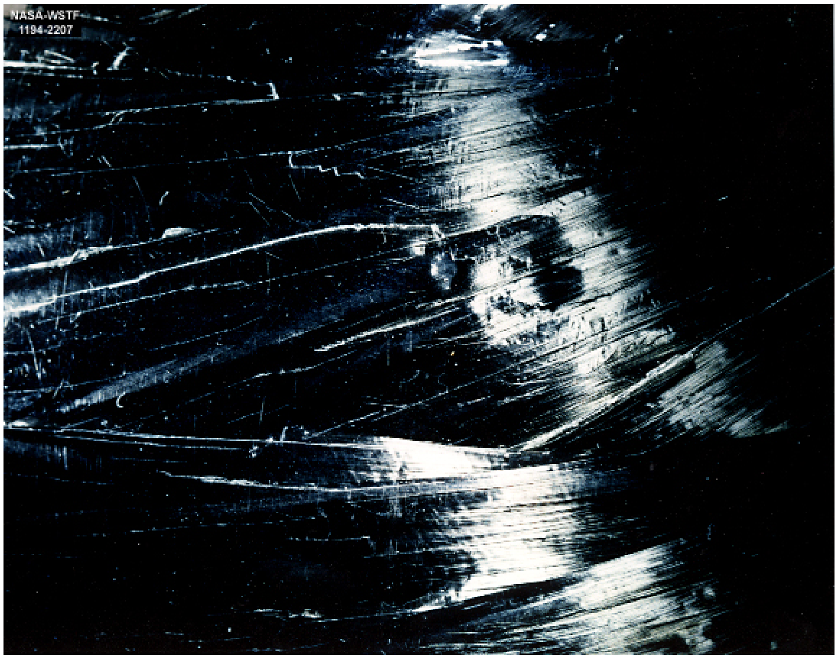
10.25 in. dia spheres

Small Sphere, Unpressurized, 25 ft-lb Impact, 0.5 in. Tup

A low energy impact to an unpressurized spherical COPV in the membrane region usually results in a shallow indentation. Note the transverse cracks emanating from the indentation edges and joining/ending at the longitudinal cracks parallel to the fiber winding direction. Typically, significant transverse cracks in the indentation itself are not found at this energy level. The concentric circular lines seen in the indentation are of unknown origin as the tup surface is basically featureless, and may be some sort of low energy resin response.

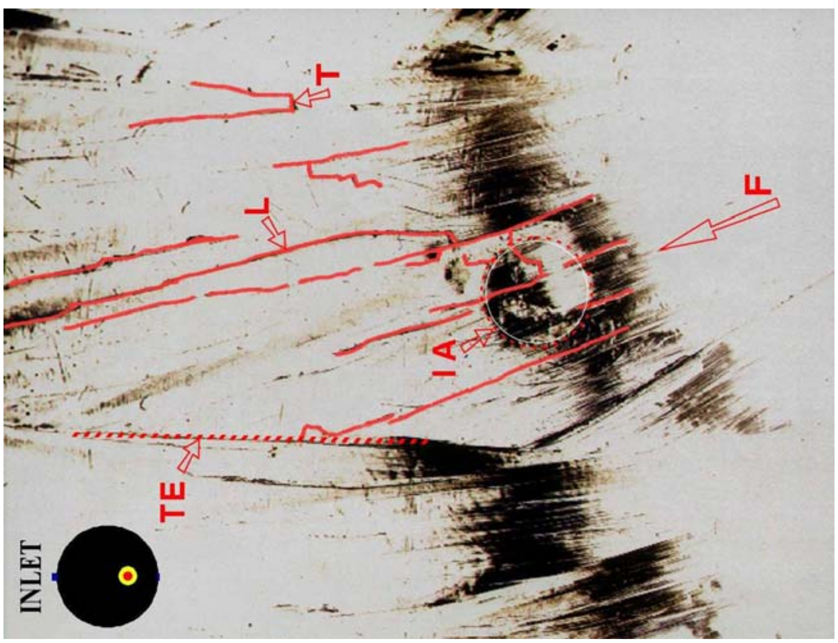
Small Sphere, Unpressurized, 35 ft-lb Impact, 0.5 in. Tup

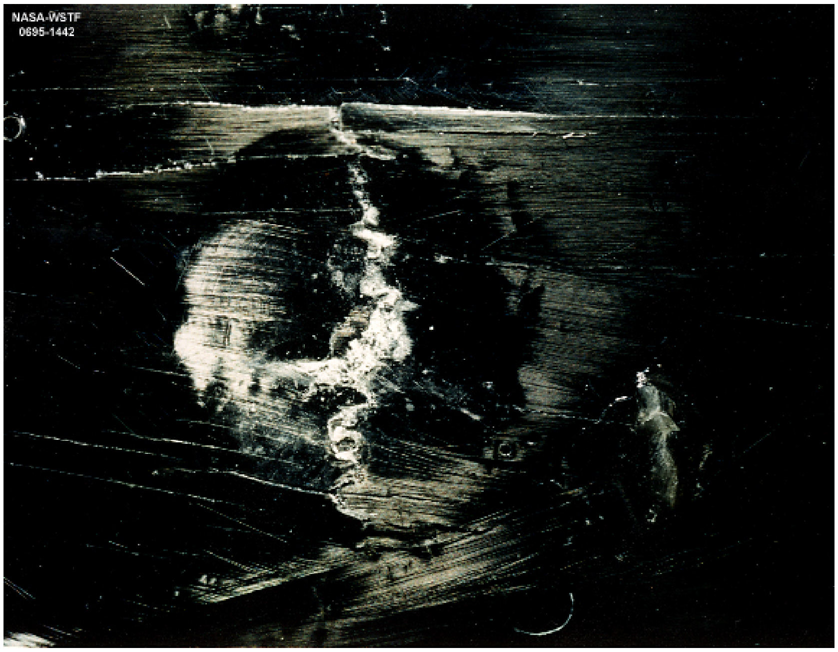
A slightly higher energy level impact than in the previous example. In this case, the vessel was impacted at the damage threshold level, which resulted in more widespread cracking in and around the impact site. Note the transverse crack path in the impact indentation area is still discontinuous. This COPV failed just below its proof pressure level.



Small Cylinder, Unpressurized, 50 ft-lb Impact, 0.5 in. Tup

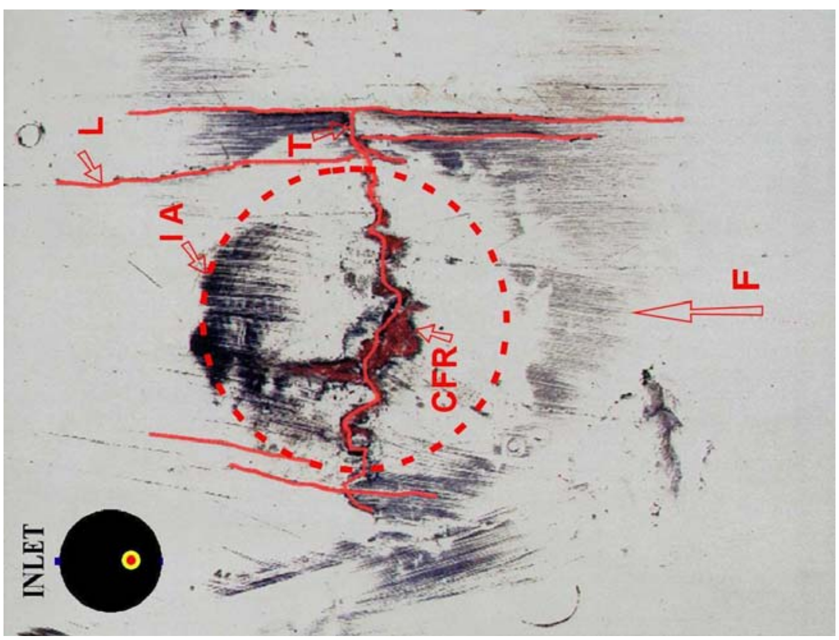
A higher energy impact to an unpressurized spherical COPV. Visible damage is not significantly different (or worse) than previous examples, but the resultant burst was well below the proof pressure. This is a good example of the statistical variation in visible damage. Even for a given energy level, several impacts can vary from easily detected to almost invisible and still have a significant effect on strength degradation.

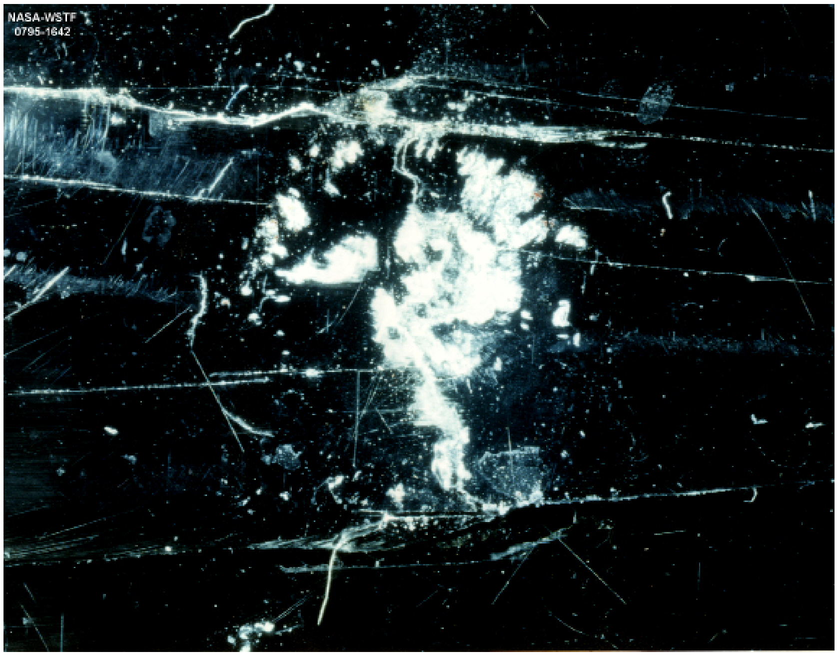




Small Sphere, 6000 psi Hydraulic, 35 ft-lb Impact

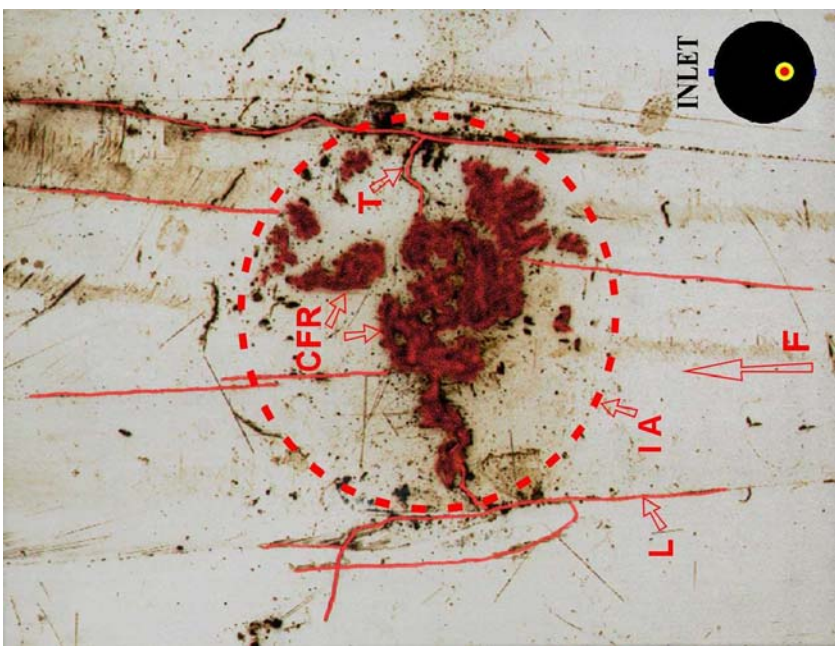
An impact to a hydraulically pressurized to MEOP spherical COPV in the membrane region normally results in a highly detectable impact indentation with full width transverse cracking. Outside the indentation, transverse cracking continues until joining/ending at longitudinal cracks that are running parallel to the fiber winding directions. This impact energy level, again represents the damage threshold level.





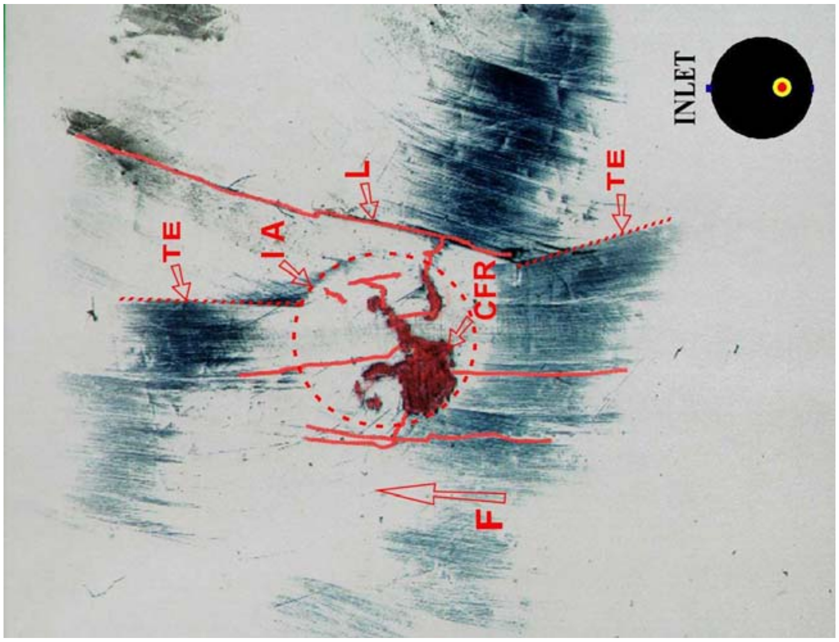
Small Sphere, 6000 psi Hydraulic, 35 ft-lb Impact

Another example of the same type of impact conditions as the previous one. Damage associated with the impact site is slightly more detectable under oblique lighting conditions.

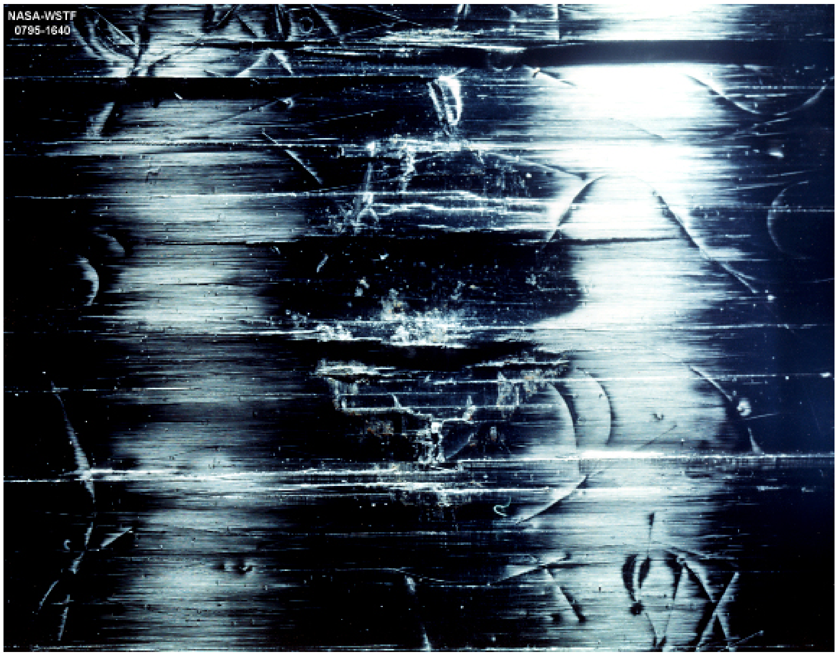


Small Sphere, 6300 psi Pneumatic, 35 ft-lb Impact, 0.5 in. Tup

Another example of the same type of impact conditions as previous only now using direct lighting. Indentation and transverse cracking are easily detected only not as clearly highlighted as before. Using both has a definite advantage.

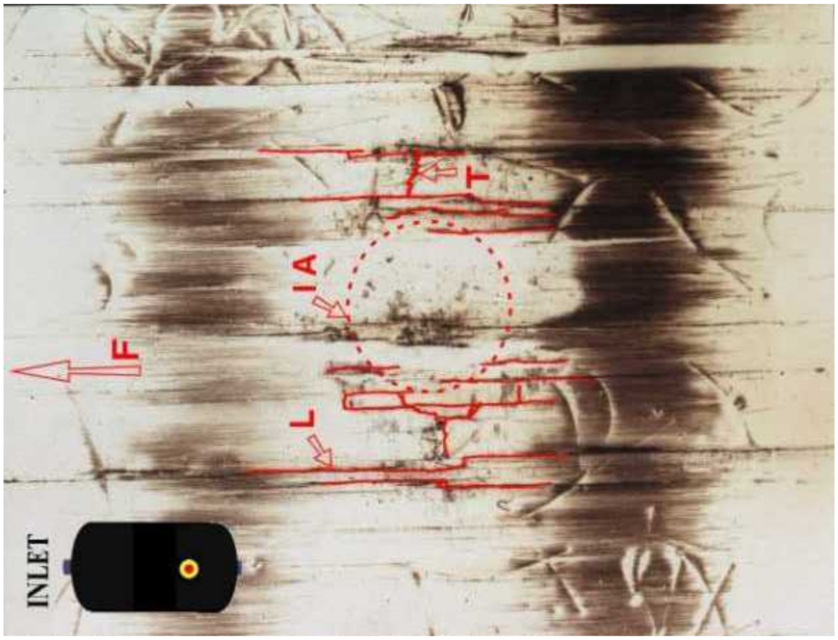


13 x 25 in. cylinders



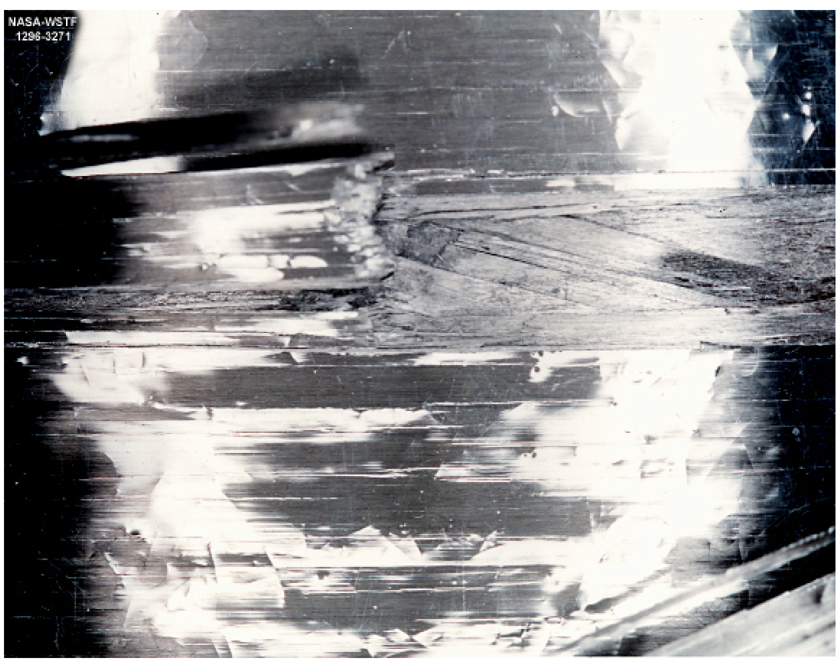
Large Cylinder, Unpressurized, 50 ft-lb Impact, 0.5 in. Tup

A slightly higher than damage threshold level impact energy example conducted on a large cylindrical COPV in the unpressurized condition. Lower level impacts produced very little visible damage. Damage seen consists of a shallow indentation with little or no transverse cracking. Longitudinal cracking is evident.



Large Cylinder, Unpressurized, 65 ft-lb Impact, 0.5 in. Tup

The impact energy level here is almost twice the damage threshold level of 35 ft-lb. Transverse cracking is now both significant and highly visible. Tow separation is evident, and some delamination has occurred. Burst occurred well below the COPV's proof pressure.

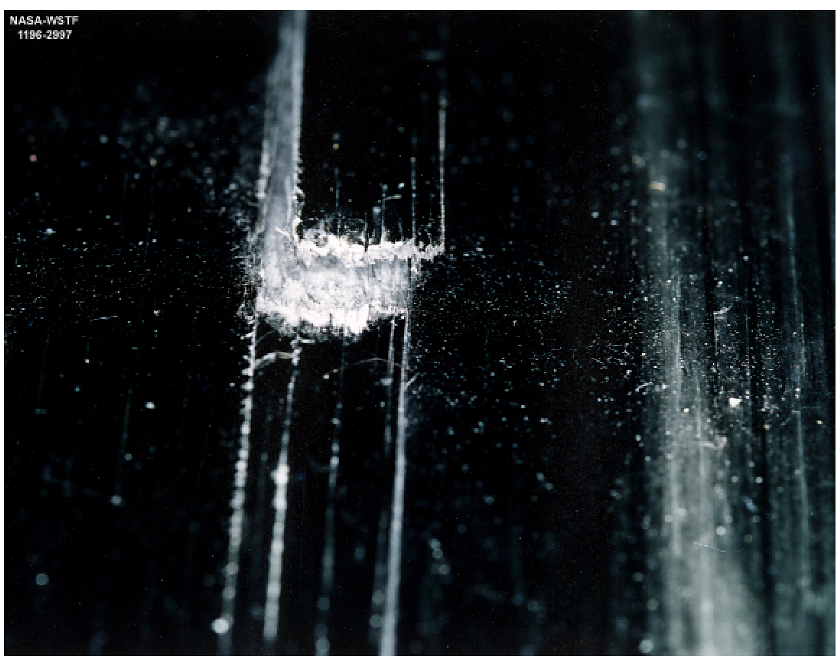


Large Cylinder, 4500 Hydraulic, 35 ft-lb Impact, 0.5 in. Tup

An impact to a hydraulically pressurized to MEOP large cylindrical COPV in the hoop region resulted in full fiber tow breakage, delamination and detachment. Clearly seen is the angular cross-tow winding pattern of the next fiber layer down. This COPV burst slightly above proof.

Large Cylinder, 4500 Hydraulic, 35 ft-lb Impact, 0.5 in. Tup, Direct Lighting

This photo shows damage photographed using direct lighting. Overall damage is visible, and fiber tow fracture and delamination is evident.



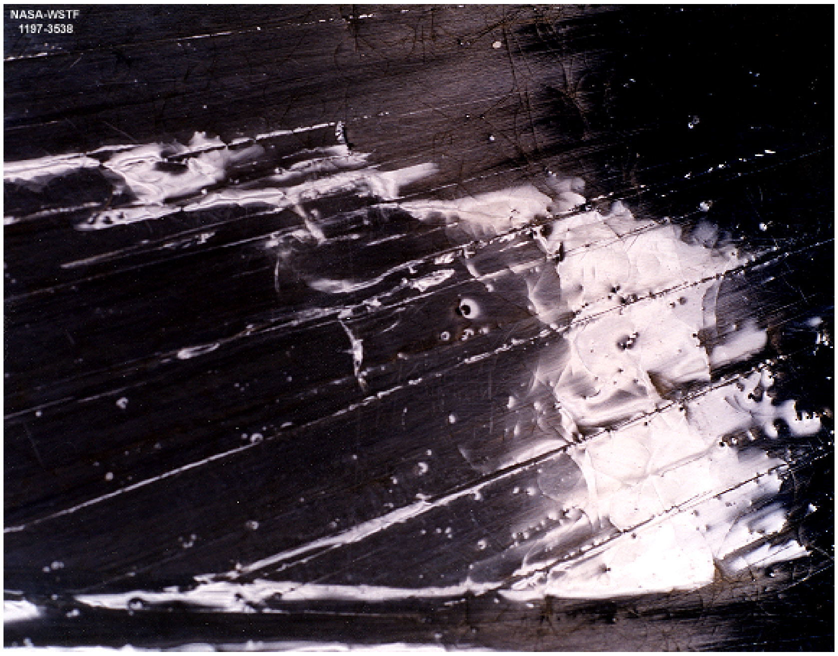
Large Cylinder, 4500 Hydraulic, 35 ft-lb Impact, 0.5 in. Tup, Oblique Lighting

The photo is the same impact site using oblique lighting. Note how change of light angle highlights fracture and cracking. COPV surface is now in black body condition.

Large Cylinder, 4500 Hydraulic, 35 ft-lb Impact, 0.5 in. Tup,
Oblique View in Direct Light

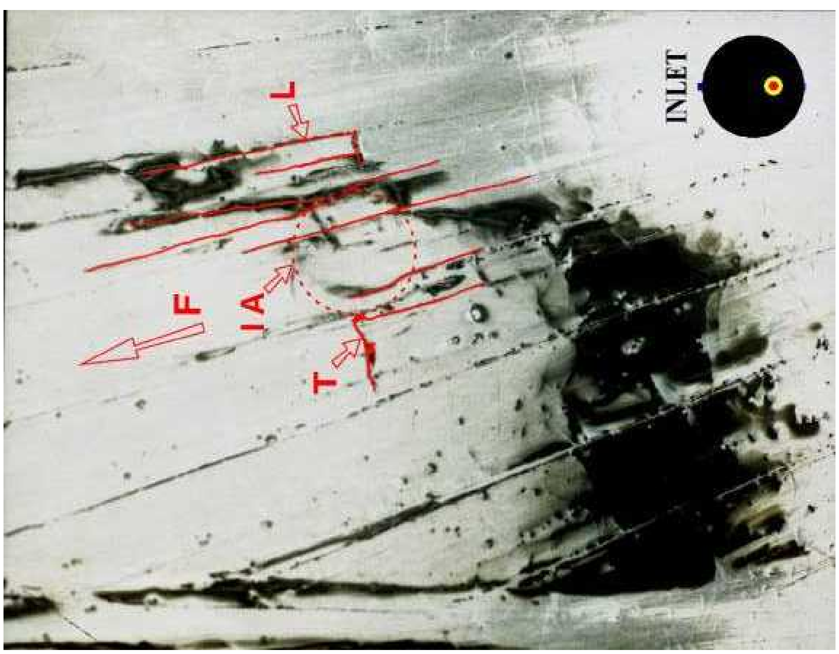
This photo of the same impact site viewed from an angle, with substantially direct lighting, shows fiber tow fracture and detachment as highly visible. It is critical to continually vary lighting and angle of view in order to see COPV damage.

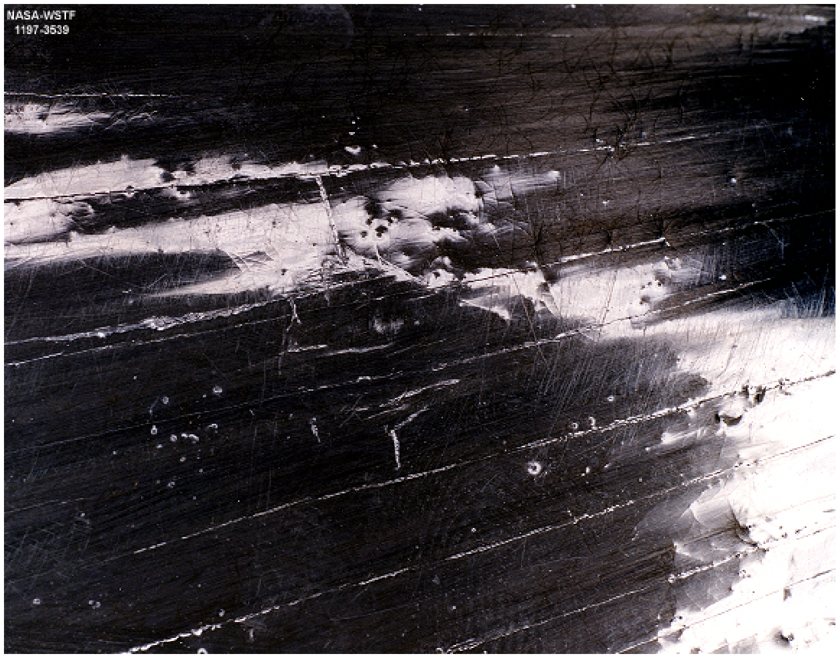
19 in. dia spheres



Large Sphere, Unpressurized, 25 ft-lb, 0.5 in. Tup

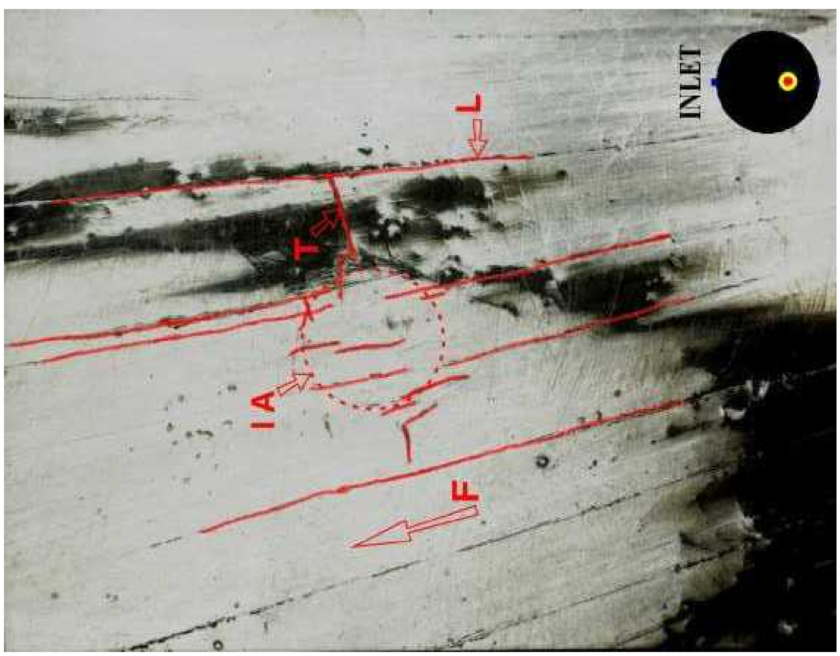
A low energy impact to an unpressurized large spherical COPV in the membrane region is almost undetected except for some associated fracture.

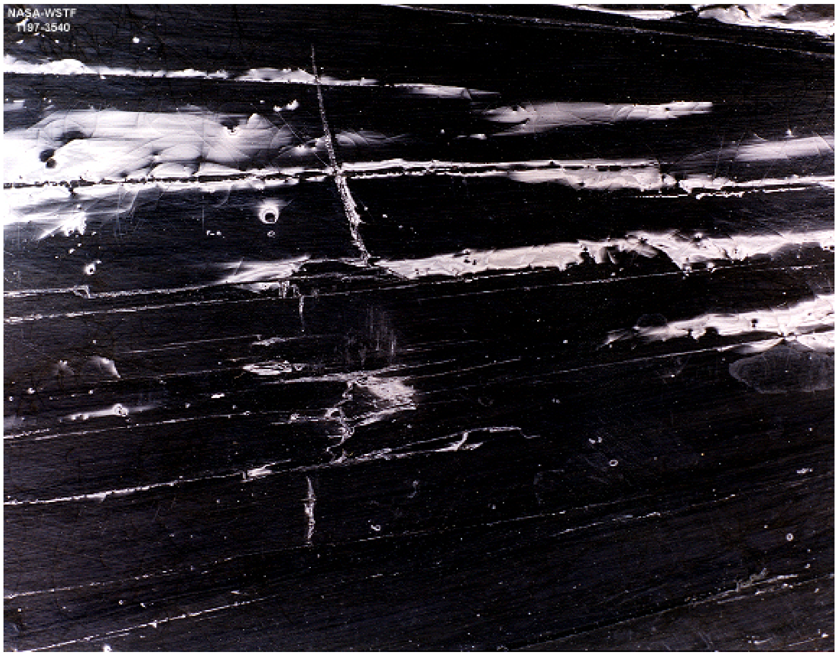




Large Sphere, Unpressurized, 35 ft-lb Impact, 0.5 in. Tup

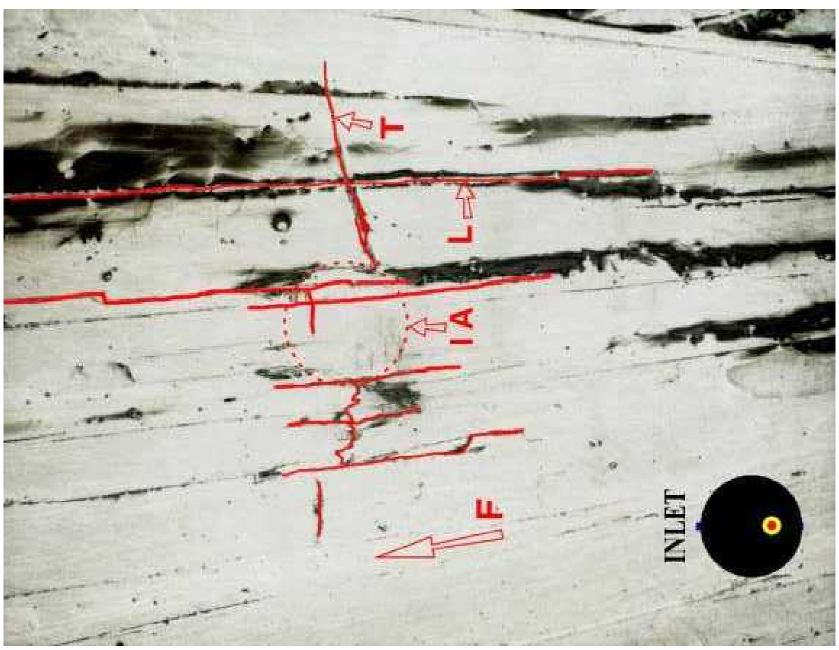
A slightly higher impact energy to the same COPV (different location) produces some visible transverse cracking.





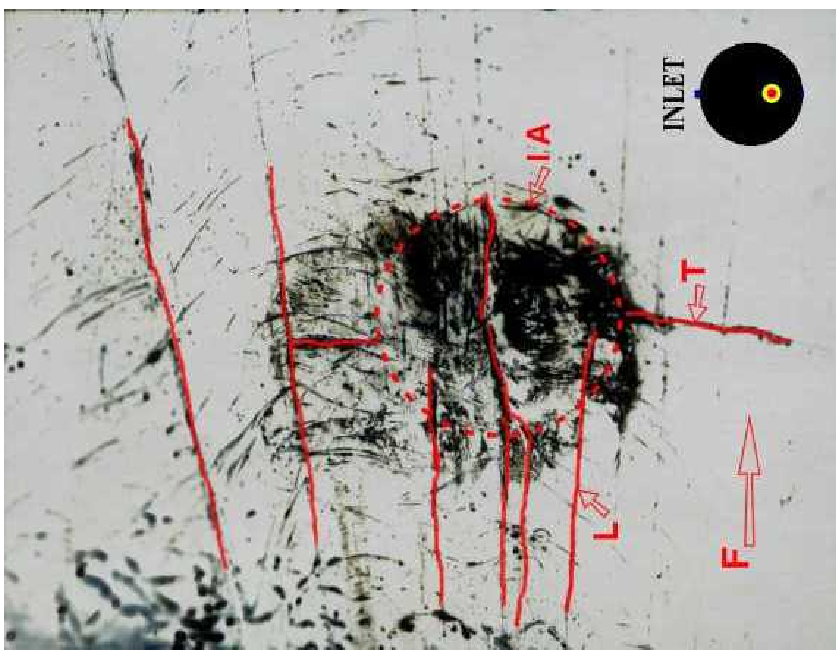
Large Sphere, Unpressurized, 45 ft-lb Impact, 0.5 in. Tup

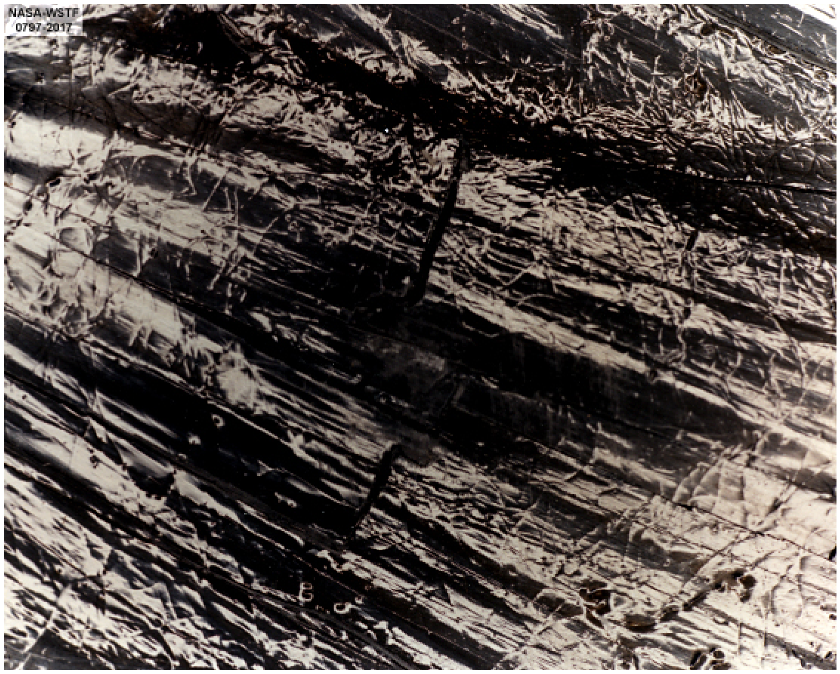
A shallow indentation is now barely visible at a slightly higher energy level. Associated transverse cracking is visible connecting up with longitudinal cracks in the traditional manner.



Large Sphere, Unpressurized, 100 ft-lb Impact, 0.5 in. Tup

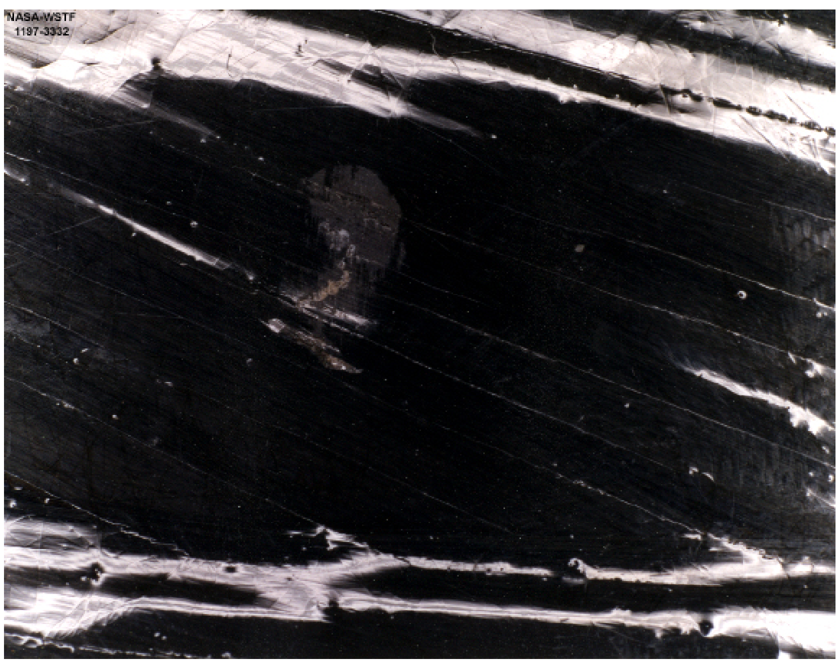
A damage threshold energy level impact to an unpressurized large spherical COPV in the membrane region produces a highly visible traditional impact damage site (indirect light).





Large Sphere, Unpressurized, 100 ft-lb Impact, 0.5 in. Tup

Another example of the same kind of impact conditions as previous (direct light).

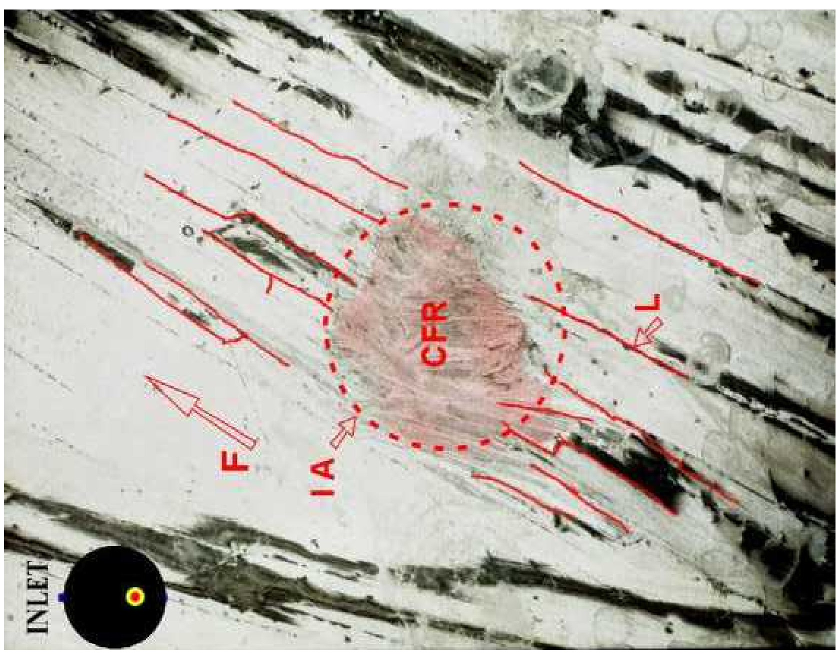


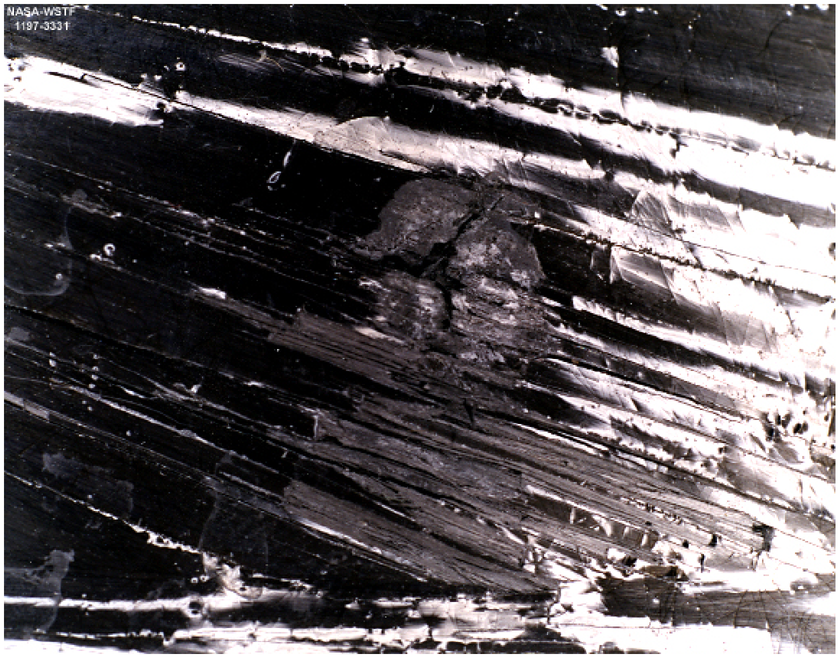
Large Sphere, 4500 psi Hydraulic, 5 ft-lb Impact, 0.5 in. Tup

A very low energy impact to a hydraulically pressurized to MEOP large spherical COPV in the membrane region results in a just visible impact indentation, with some slight associated cracking. This could be easily missed.

Large Sphere, 4500 psi Hydraulic, 15 ft-lb Impact, 0.5 in. Tup

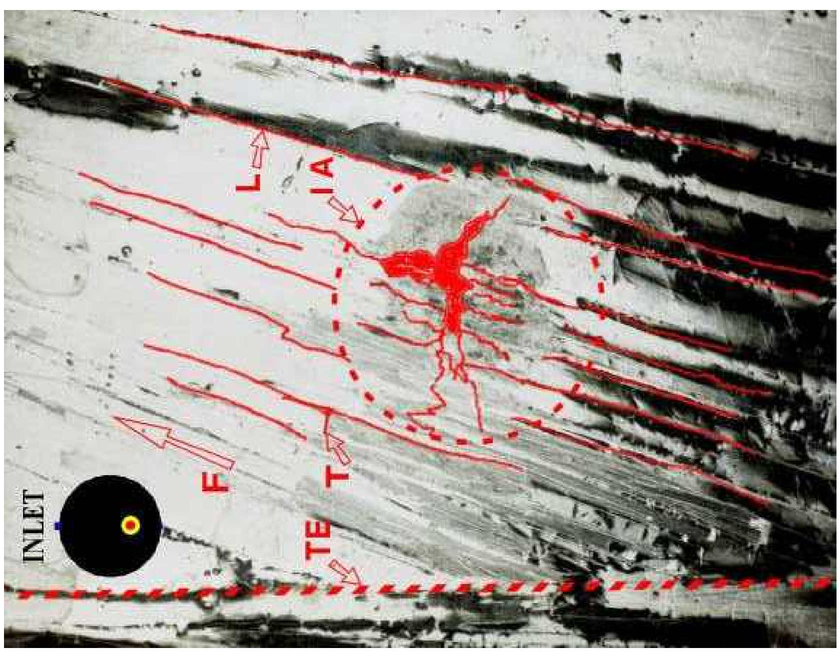
A slightly higher impact energy level produces clearly evident mashed and distorted fiber in the damage site.

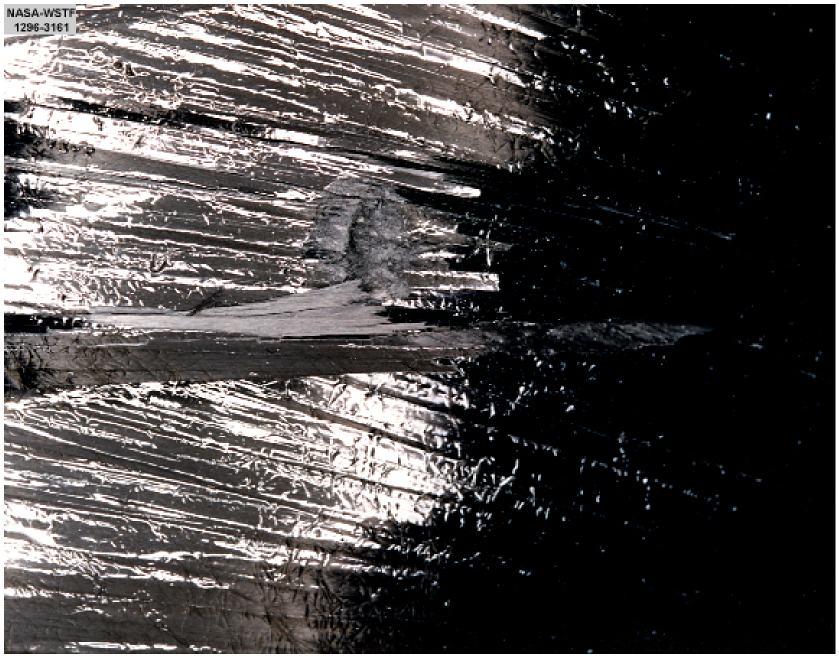




Large Sphere, 4500 psi Hydraulic, 35 ft-lb Impact, 0.5 in. Tup

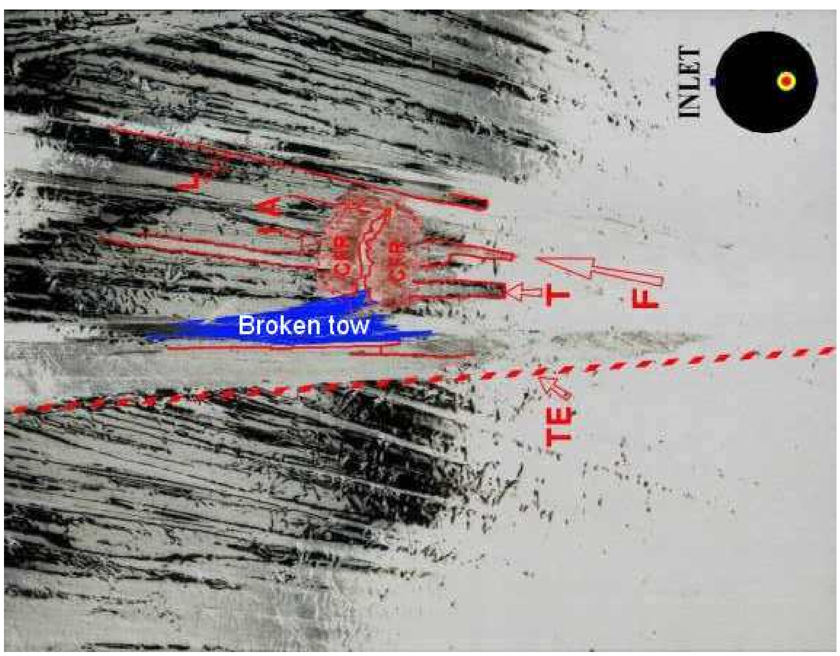
An even higher impact energy level produces more of a traditional impact damage site with both transverse and longitudinal cracking. Compared to the unpressurized condition, one clearly sees the visible damage added due to pressurization.

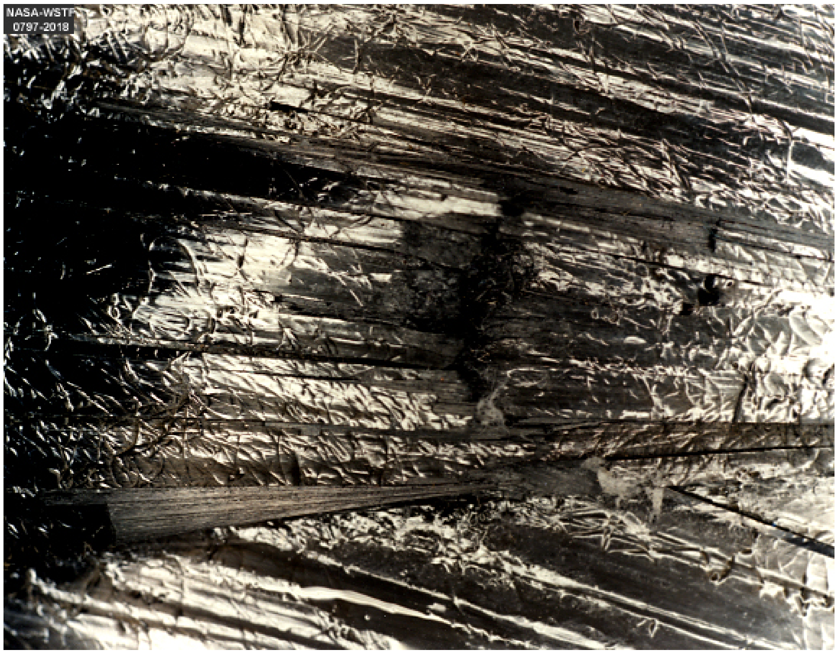




Large Sphere, 4725 psi Pneumatic, 100 ft-lb Impact, 0.5 in. Tup

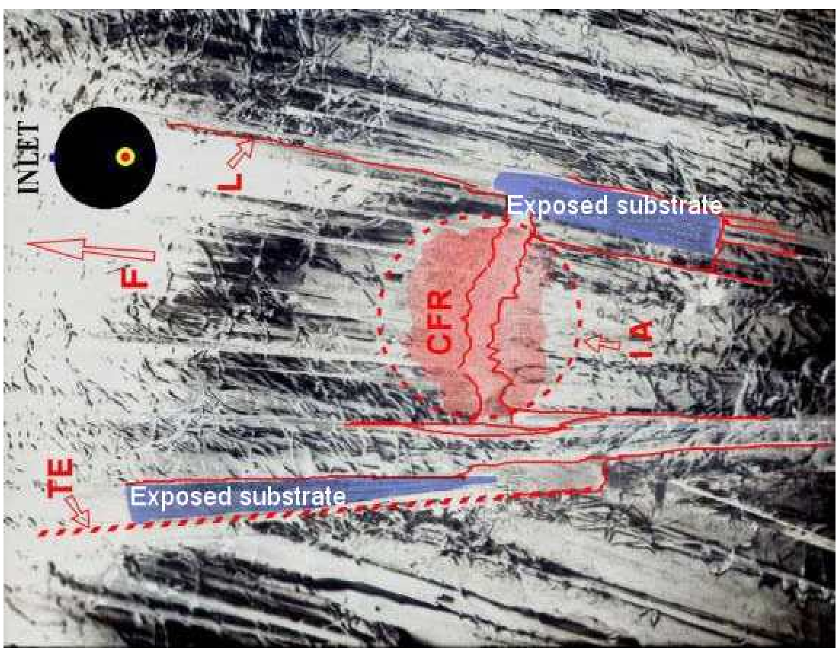
An impact to a pneumatically pressurized to MEOP large spherical COPV in the membrane region results in a highly visible damage site composed of transverse fracture, tow detachment and delamination.



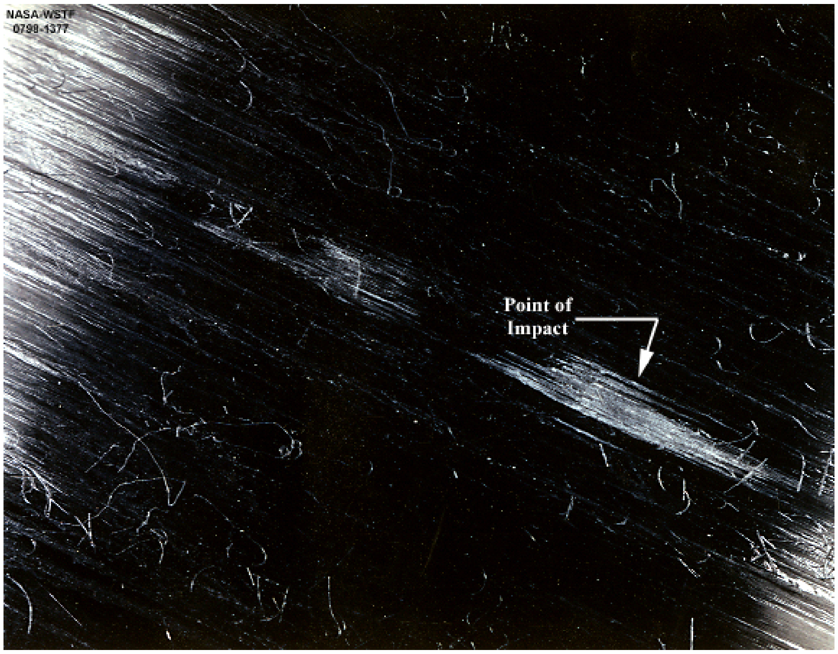


Large Sphere, 4725 psi Pneumatic, 100 ft-lb, 0.5 in. Tup

An impact to a pneumatically pressurized to MEOP large spherical COPV in the membrane region results in a highly visible damage site composed of transverse fracture, tow detachment, longitudinal cracking, and delamination.

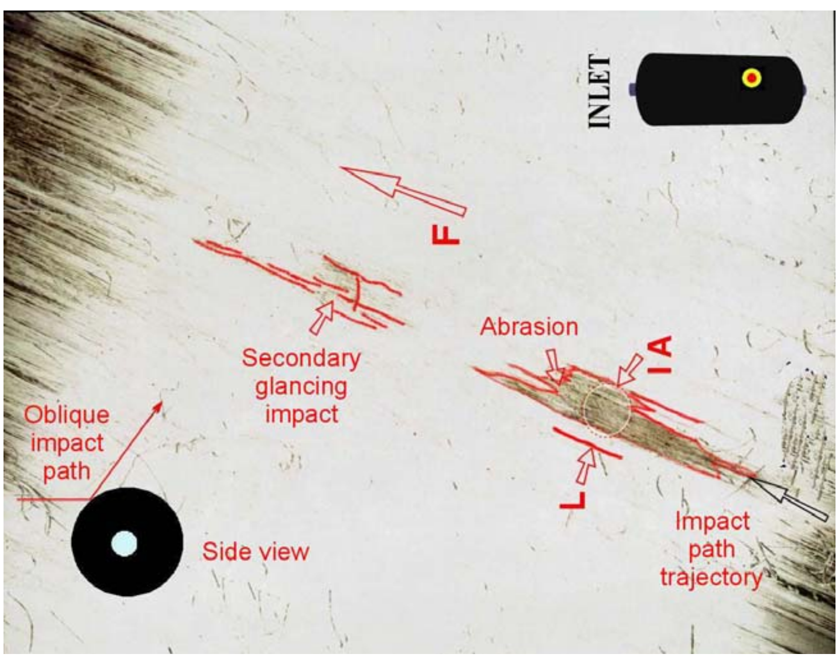


6.6 x 20 in. cylinder, oblique



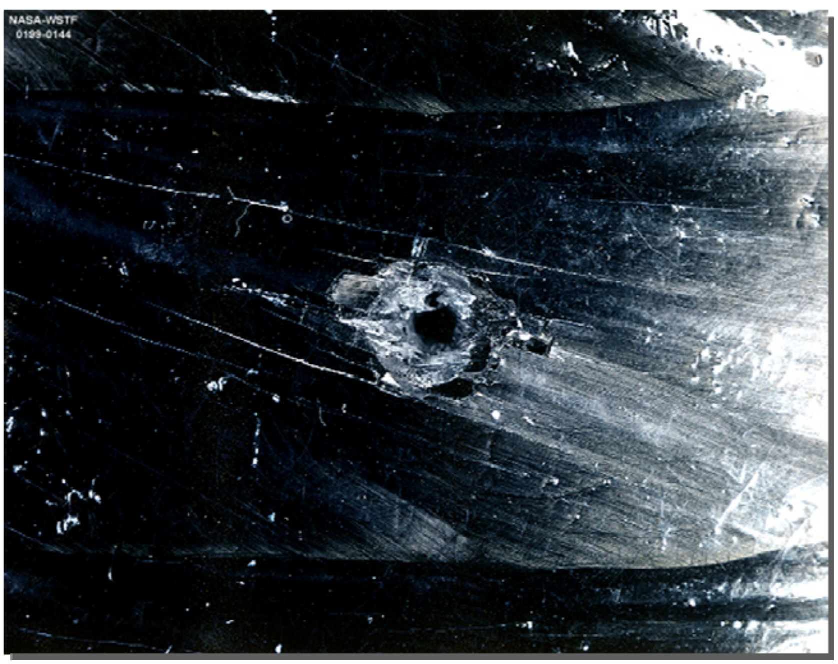
Small Cylinder, Unpressurized, Oblique Impact, 0.5 in. Tup

Shown is the case of an oblique (~45º) impact in the hoop region of an unpressurized cylindrical COPV. Initial impact is seen as a very pronounced scuff or smear. The point of impact is seen with some slight cratering or sliding type indentation with a second slight impact just ahead of it. This damage, while significant had no measurable effect on COPV burst strength. This example is shown as it represents a "real world" impact, such as that from the glancing blow of a dropped tool.

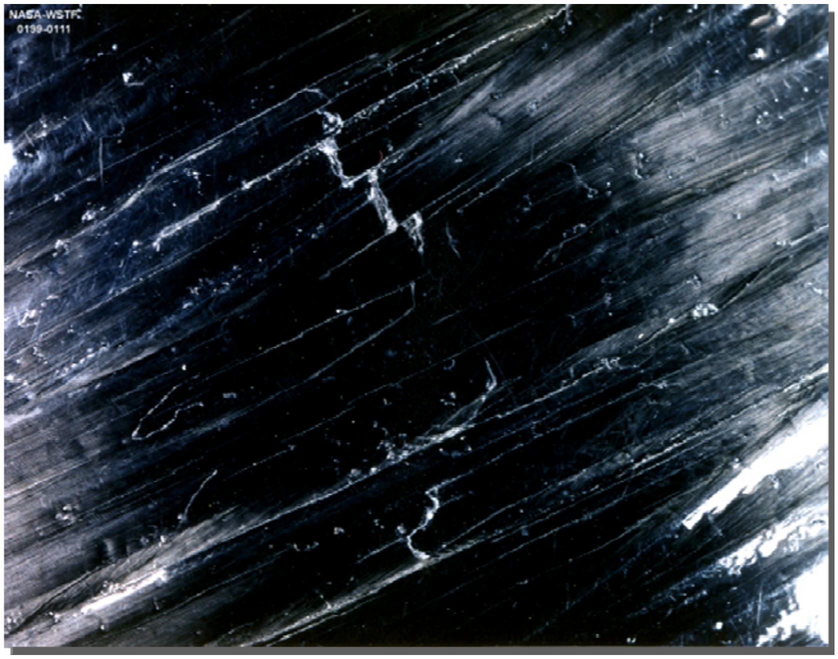


Visual Inspection Photos

Small sphere, unpressurized, screwdriver tup



Small sphere, unpressurized, 0.25 in. hemispherical tup



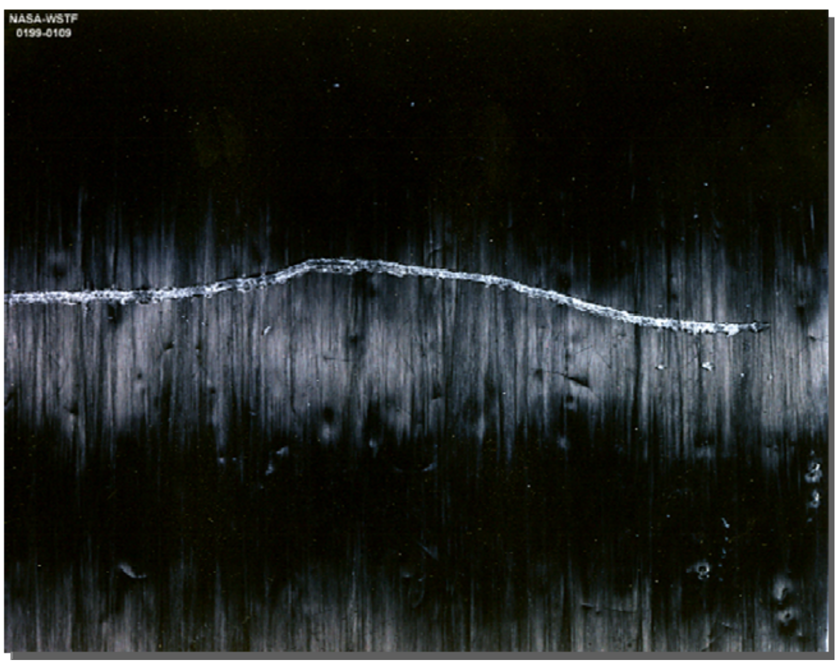
Small sphere, unpressurized, wide field cracking

Small cylinder, manufacturing defect, nonelastic end crack

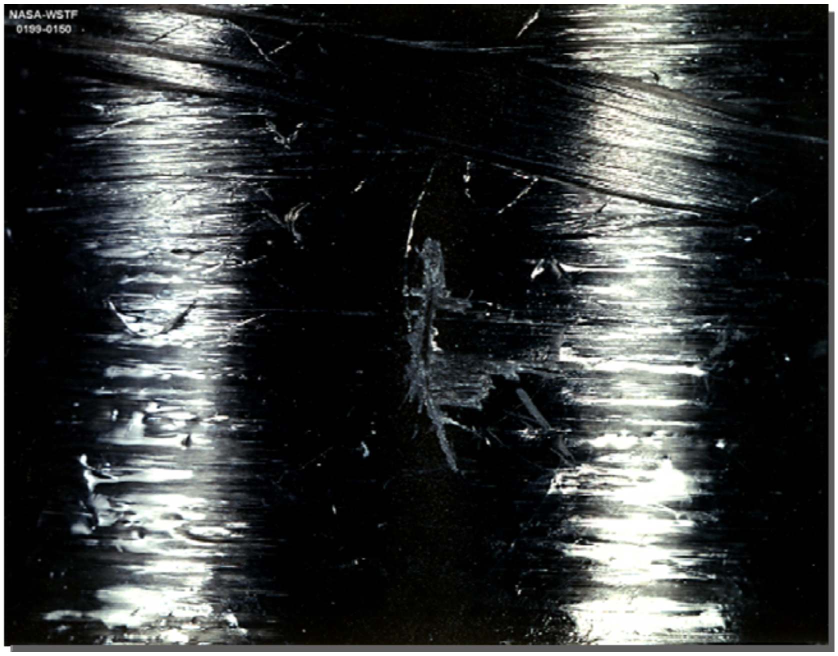
Small cylinder, scratch, transverse to winding direction

Small cylinder, significant scratch, transverse to winding direction

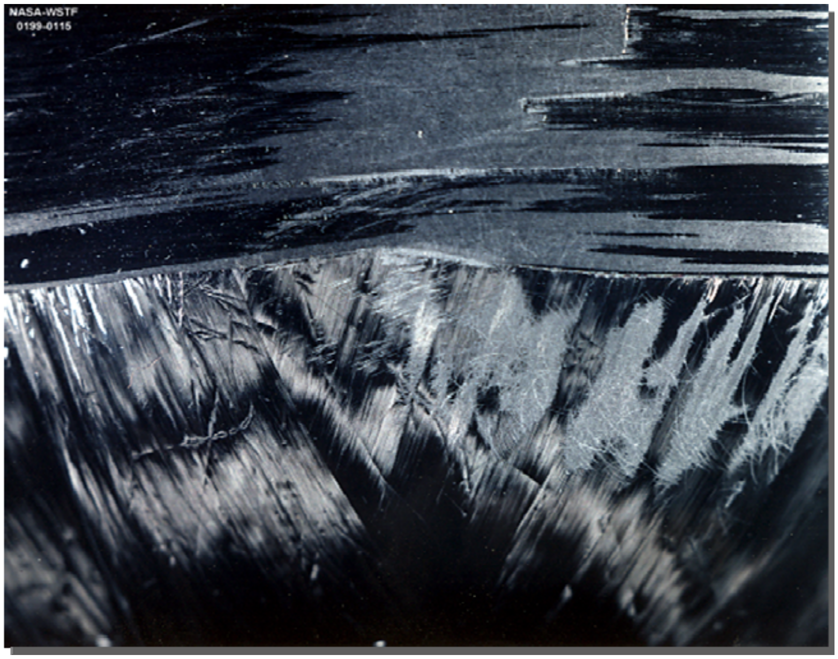
Small cylinder, cut, transverse to winding direction



Small cylinder, significant cut, transverse to winding direction



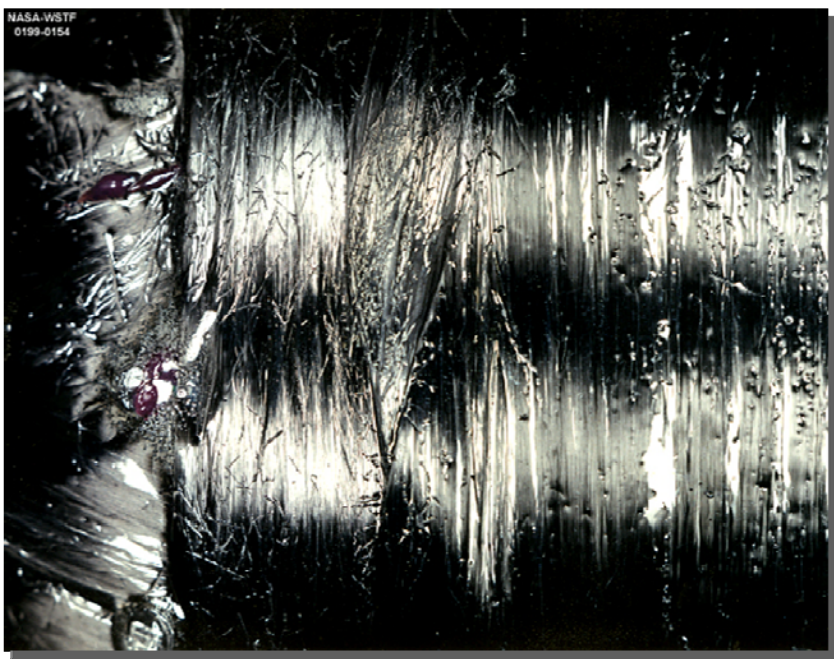
Small sphere, deep cut, transverse to winding direction



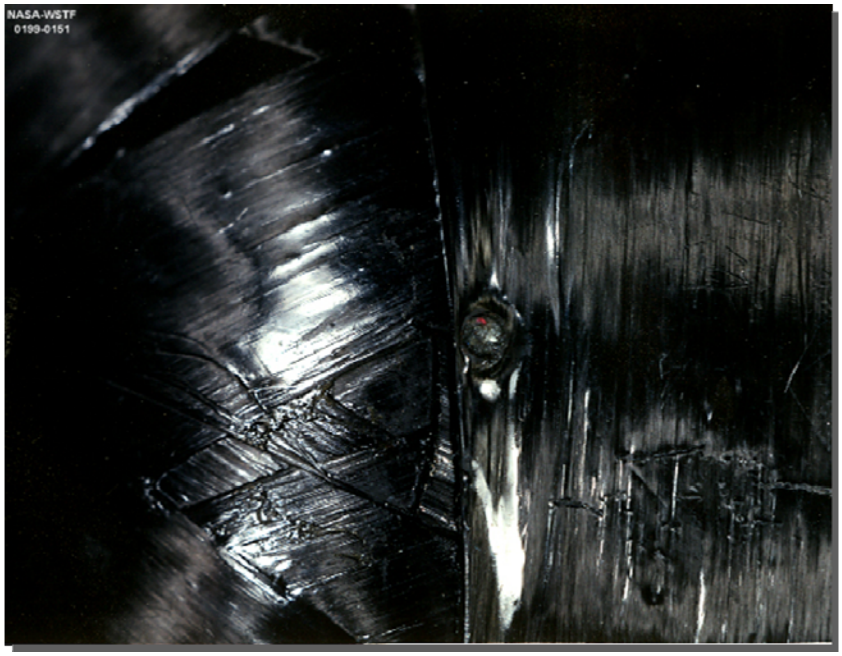
4.6 x 10 in. cylinder, abrasion

4.6 x 10 in. cylinder, significant abrasion

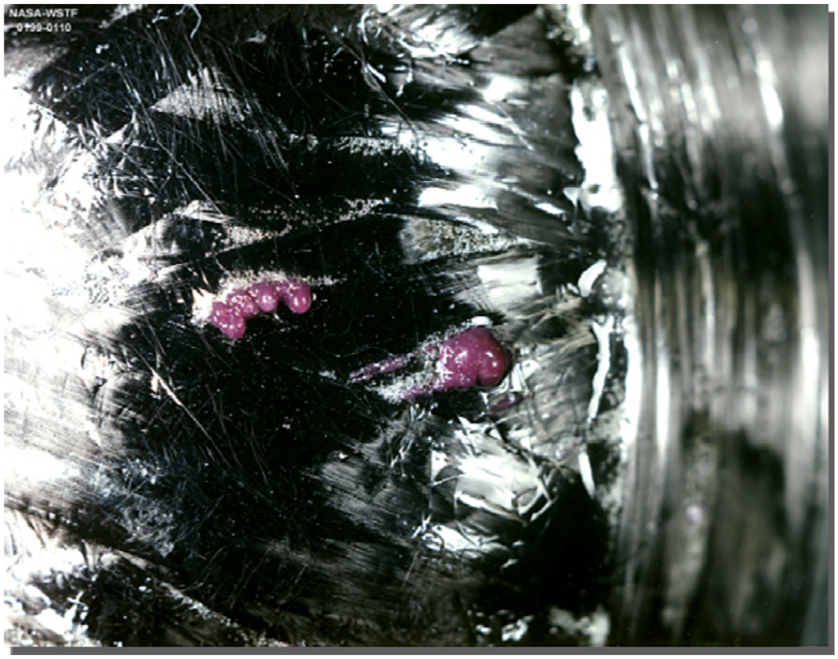
Small sphere, abnormal tie-off



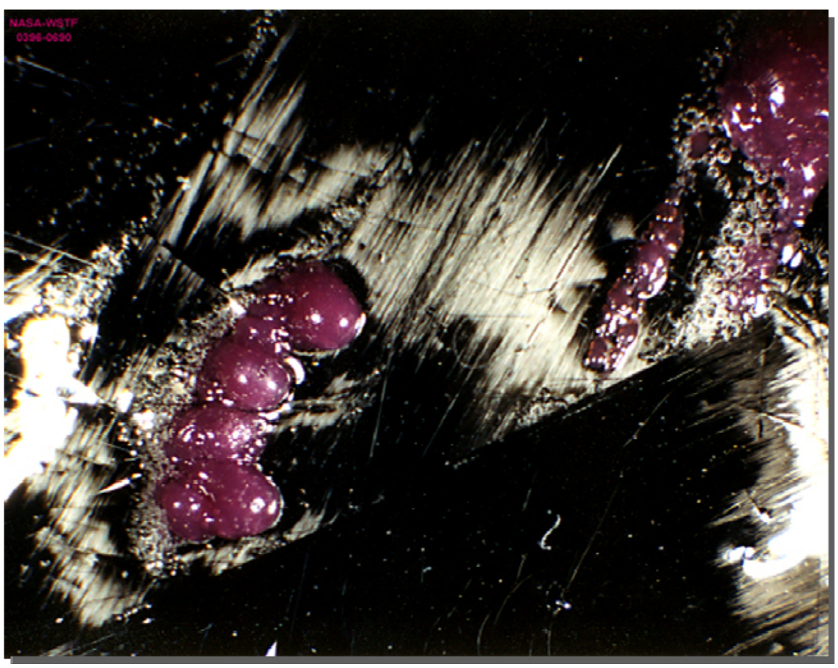
4 x 9 in. cylinder, normal tow termination



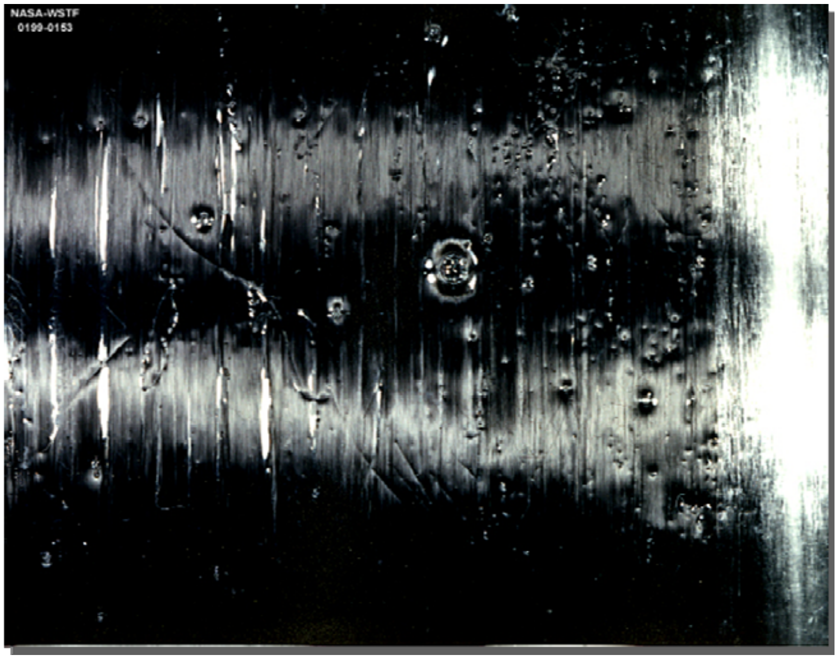
4 x 9 in. cylinder, broken tow



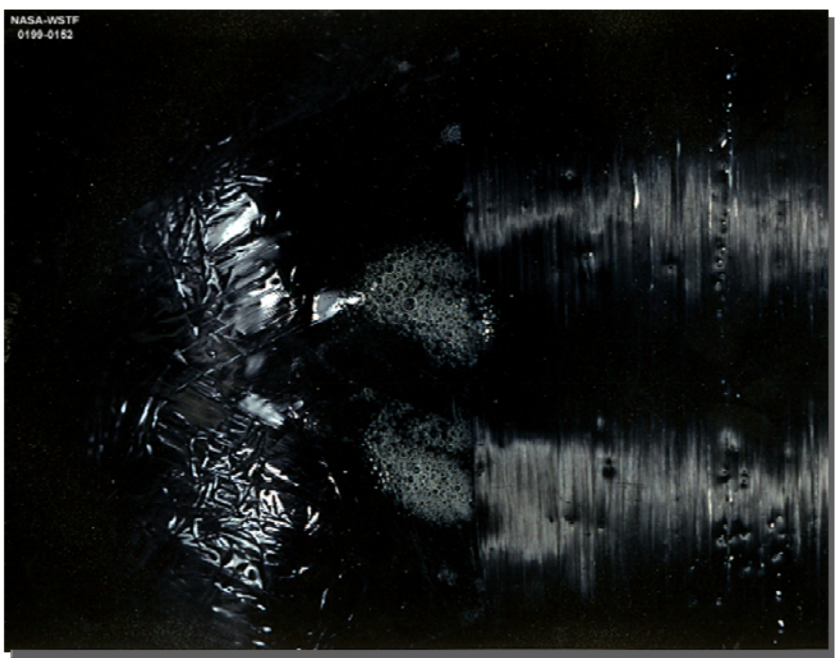
4 x 9 in. cylinder, excess bonding agent



4 x 9 in. cylinder, excess bonding agent, magnified view



4 x 9 in. cylinder, surface resin indications



4 x 9 in. cylinder, surface resin porosity

4 x 9 in. cylinder, entrained fiber

Typical inlet thread

Inlet thread damage