John F. Kennedy Space Center

Composite Pressure Vessel Ground Processing Hazards and Risk Management at KSC

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Topics and Background

- Major Topics
  - COPV safety documentation (only Leak Before Burst (LBB) failure mode vs. current COPV failure modes/hazard causes)
  - Brief overview of the KSC Cryogenic Composite Tank Rupture Incident
  - KSC COPV ground processing hazards
    - How they were managed for the Shuttle Program
    - How they are being controlled for the International Space Station (ISS) Program
  - NASA, Air Force , and industry standards for composite pressure vessels

NASA Safety Documentation of COPV risks and LBB

- Safety documentation for Shuttle and International Space Station originally stated COPVs were "designed to have a leak before burst failure mode".
  - The safety documentation did not address other possible COPV failure modes. COPV burst due to stress rupture or impact damage of the composite was not addressed
- Per AIAA S-081, Leak-Before-Burst (LBB) is a design approach in which pre-existing flaws in the metallic liner may grow through the liner and result in pressure-relieving leakage rather than burst or rupture
  - LBB does not apply to the composite overwrap.
- Following a NASA Engineering and Safety Center (NESC) review that showed a significant risk of COPV composite stress rupture, the Shuttle program updated their flight COPV Hazard Reports and CILs to address COPV stress rupture.
- Shuttle Hazard Report "Stress Rupture of an Orbiter ECLSS, OMS/RCS, or MPS Composite Overwrapped Pressure Vessel (COPV) during Ground Processing" documented the COPV ground processing risks, mitigations, and controls.

COPV Failure Modes

- To correct this for ISS COPVs, Scott Forth/ NASA Pressure Vessel & Fracture Control Technical Monitor, issued Technical Memo ES4-08-043 Composite Overwrapped Pressure Vessel (COPV) Risks which states:

"Failure of a COPV may be catastrophic, leading to loss of the vehicle, ground personnel, or crew, and is therefore fracture critical."

- The memo identified four failure modes associated with COPVs:
  - **Burst from over-pressurization**
    - Operationally controlled
  - **Fatigue failure of the metallic liner**
    - Test data shows this risk to be low for KSC operations for most ISS COPVs.
    - This risk may be higher for NORS COPVs due to Inconel welded liner.
  - **Burst resulting from damage to the metallic or composite**
    - Failure of the COPV from damage to the composite is mitigated by the Damage Control Plan and damage tolerance testing.
  - **Stress rupture of the composite overwrap**
    - To date, the composite stress rupture failure mode of the ISS COPVs has not been adequately mitigated. COPV stress rupture is a sudden failure mode that can occur at normal operating pressures and temperatures, while at stress levels below ultimate strength. It can produce significant overpressure/ blast wave and fragmentation/shrapnel.

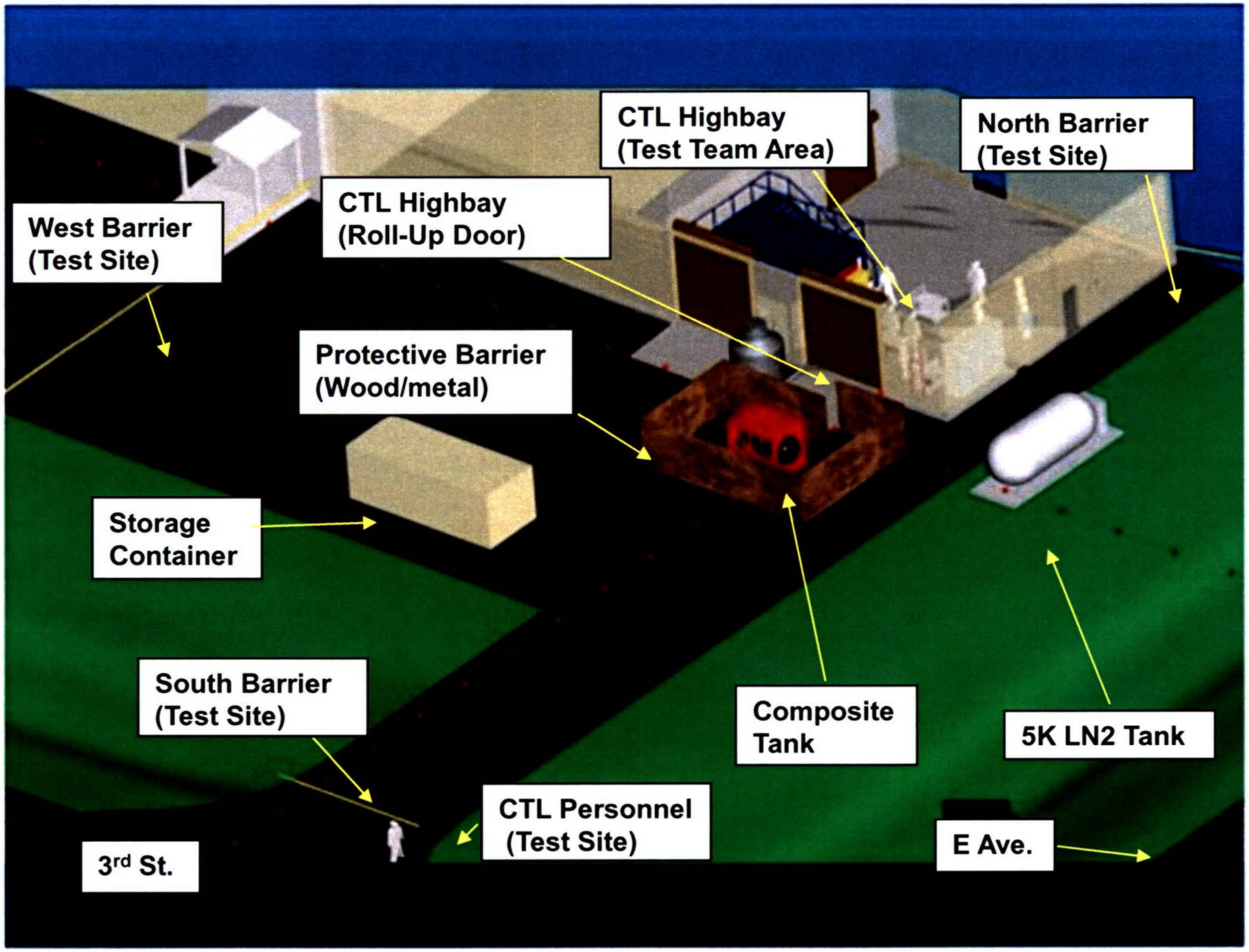
Cryogenic Composite Tank Rupture Incident at KSC

- On December 23, 2008 a composite pressure vessel (no liner) burst during pressure testing while filled with LN2 (~900 gal.) and pressurized with GN2. The test team expected a **leak-before-burst** failure and failed to take into account additional energy potential including **BLEVE** (Boiling Liquid Expanding Vapor Explosion).
- The test team thought they were protected by plywood barriers and a roll-up door. However a high velocity jet of LN2 impacted and opened the door, directly contacting 4 team members and filling the room with N2. Several team members received mild cryo burns, one member received a cracked rib, 2nd degree cryo burns and other injuries. The test team was fortunate, they could have suffered much worse consequences.

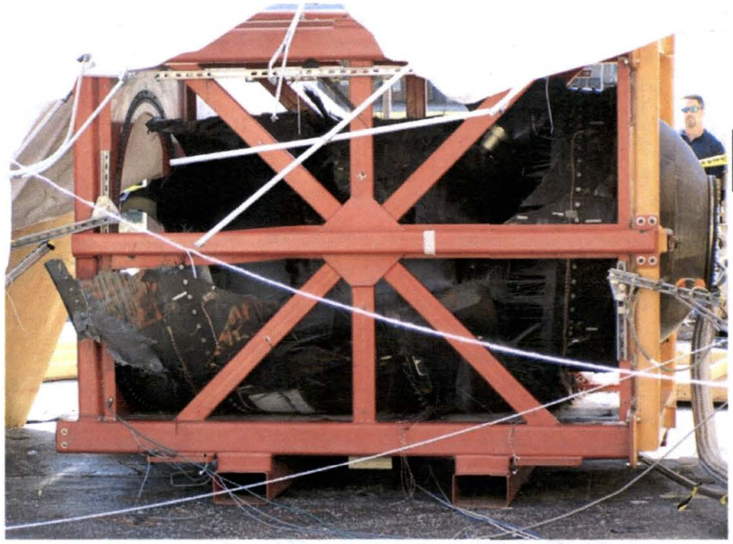
Test Unit Plywood Protective Barrier Under Construction

Area surrounding test unit following tank rupture. Test team location was behind roll-up door at top of image.

Cryo Tank Pre-Test Set-up



Post-Rupture



CTL Exterior

Cryo Tank

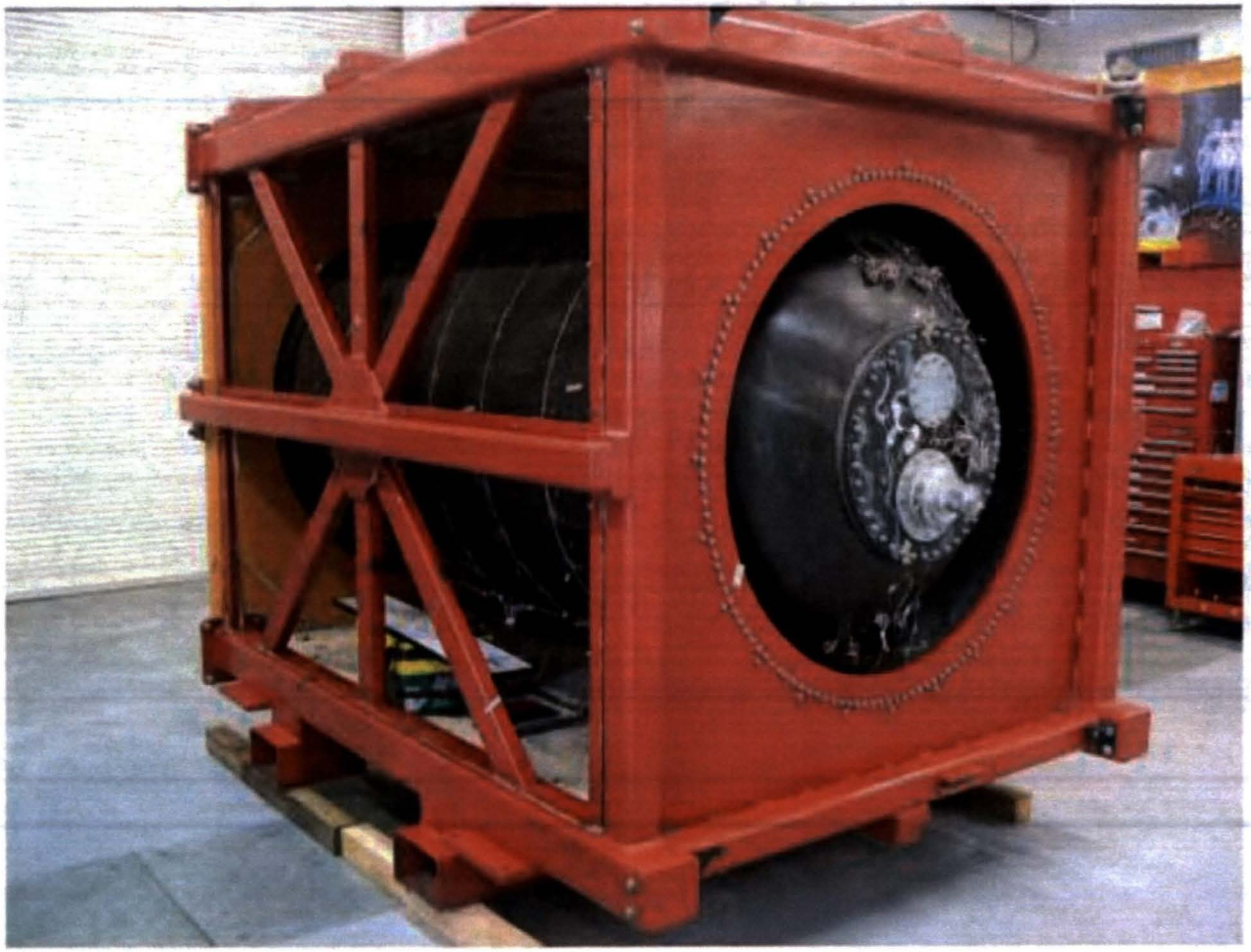


Figure 2-2. Composite Tank in Support Structure

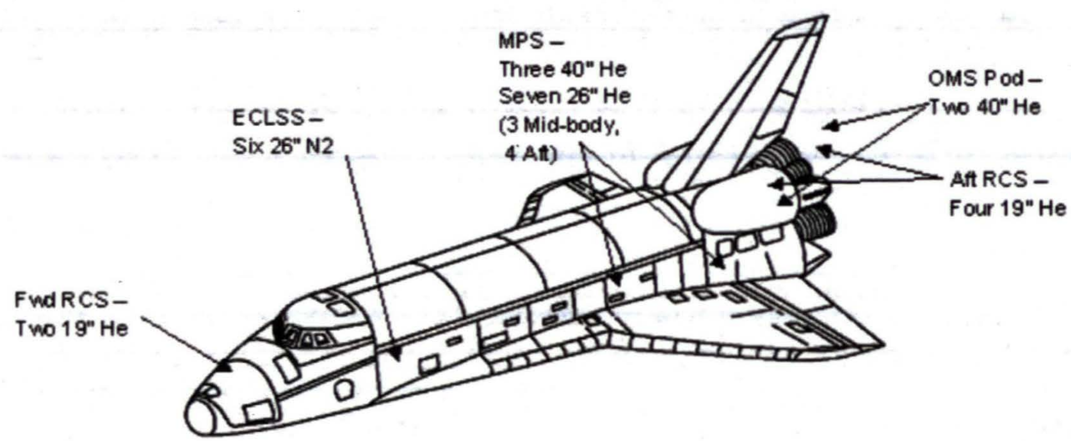
Cryogenic Composite Tank Rupture

Mishap Investigation Report Findings:

- The pretest analysis was in error regarding the total energy available during a failure; it only considered the pneumatic energy of the 10% by volume ullage space.
- There was no blast/fragmentation or QD siting analysis of barrier capabilities, plywood, or door.
- The Test Team accepted the manufacturer's CPV structural analysis without sufficient review.
- The manufacturer of the tank maintained it would fail by a Leak Before Burst scenario without supporting evidence, as did the test team in its Test Readiness Review.

Orbiter COPV Processing Risk Management

- COPVs on the Shuttle Orbiter were Kevlar/Epoxy overwrapped, with one graphite Epoxy COPV.
- Based on the Orbiter COPV working group stress rupture risk calculations for Orbiter COPVs, COPV Stress Rupture became a top Shuttle program risk. Significant changes were made to reduce the ground processing risk to personnel :
  - Modified pressurization of COPVs to limit temperature and fiber stress
  - The pad was cleared during COPV pressurization
  - The KSC COPV Safety Bulletin limiting pad access to essential personnel from L-4 to launch was broadcast through out KSC
  - Several COPVs from Orbiters with highest stress rupture risk were replaced
  - Reduced OMS flight pressures for remaining flights
  - WSTF performed burst and stress rupture tests of existing Orbiter COPVs and blast analysis



Orbiter COPV risk from 10/18/2007 PRCB

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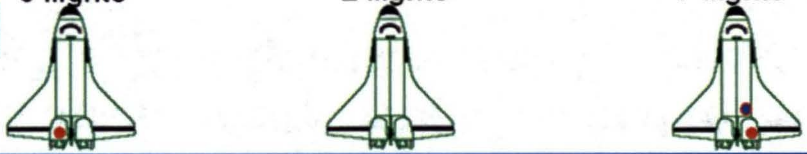
Life of Program Reliability Estimate

Two Day Launch Scrub - PRCB 10/18/2007

From STS-118

	OV-103 6 flights			OV-104 2 flights			OV-105 7 flights			Life of Program COPV Reliability 15 Flights Combined	
											

Per Flight* Reliability Numbers	OMS Full	OMS Reduced		OMS Full	OMS Reduced		OMS Full	OMS Reduced			
Point	.999 66	.999 89		.999 994	.999 997		.999 85	.999 944	=	.998 6	1:710
Mean	.999 53	.999 84	+	.999 989	.999 995	+	.999 78	.999 918		.998 0	1:489
95% CL	.998 3	.999 42		.999 958	.999 978		.999 20	.999 69		.992 5	1:134

Life of Program, 15 flight Failure Likelihood

Cumulative Reliability (per vehicle) From # of Flights	1 Flight	5 Flight	1 Flight	1 Flight	1 Flight	6 Flight
Point	0.999 09	1:1,099	0.999 991	1:111,111	0.999 51	1:2,041
Mean	0.998 7	1:769	0.999 984	1:62,500	0.999 27	1:1,370
95% CL	0.995 3	1:213	0.999 936	1:15,625	0.997 3	1:370

- OMS tank s/n 020 in RP03 is the driver for OV-103 reliability numbers
- OMS tank s/n 018 in LP03 is the driver for OV-105 reliability numbers
- MPS tank s/n 021 in OV-105 is a large contributor to reliability numbers

* Note that reliability for each individual flight is virtually the same for all the individual flights through the end of the Program

Note: OV-104 numbers based on replaced MPS Tanks.

USA United Space Alliance

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ISS Program COPV Processing Risk Management

- COPVs used on the ISS Element and in ISS Experiments are primarily Graphite Epoxy Composite Overwrapped:
  - ISS Element COPVs include Nitrogen Tank Assembly (NTA), High Pressure Gas Tank (HPGT), and Plasma Contactor Unit (PCU)
  - ISS Experiment COPVs include Alpha Magnetic Spectrometer (AMS-2), SPACEDRUMS (Space Dynamically Responding Ultrasonic Matrix System), JAXA Gas Bottle Assembly (GBU), Verification Gas Assembly (VGA), and Vehicle Cabin Atmosphere Monitor (VCAM)
- COPVs for the Nitrogen Oxygen Recharge System (NORS) are in the qualification phase. They were designed to ISO requirements, and have received a DOT Special Permit for transportation of pressurized COPVs.
- At KSC, ISS COPVs were remotely pressurized in an offline blast resistant facility. The primary ground processing risk to personnel was during processing in the SSPF and pad once pressurized.

Carbon COPV Reliability

- The NESC COPV Working Group was asked to determine the probability of COPV stress rupture for ISS ground processing and ISS flight operations, but due to the limited Graphite strand and vessel test data available at the time, the results of this analysis were problematic.

  "All NASA programs that use COPVs have the same basic issue: We do not have a way to adequately quantify (graphite) COPV risk with current data and models. "

  "The failure mechanism associated with stress rupture is complex, not well understood, and is difficult to accurately predict or detect prior to failure"

- To address this problem, NASA currently has an extensive COPV test program underway at WSTF to determine carbon COPV reliability.

  300 Carbon subscale COPVs manufactured by General Dynamics

  Burst Testing complete

  Sub-scale test program is on-schedule to meet NORS flight needs

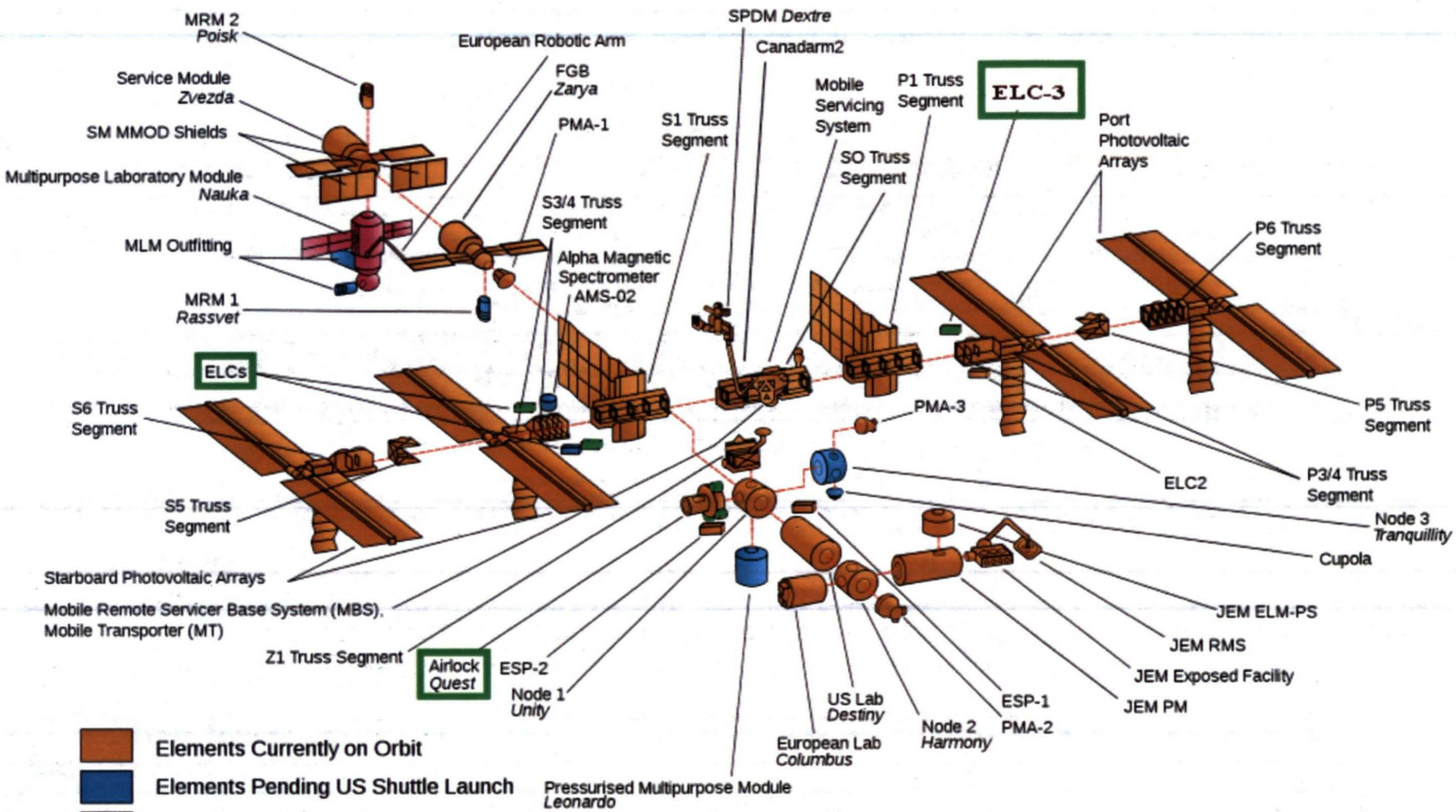
  A full scale COPV testing program is being evaluated which will reduce conservatism in reliability calculations and verify modeling assumptions

  - Flight-quality COPVs have better manufacturing process

ISS Vehicle COPVs

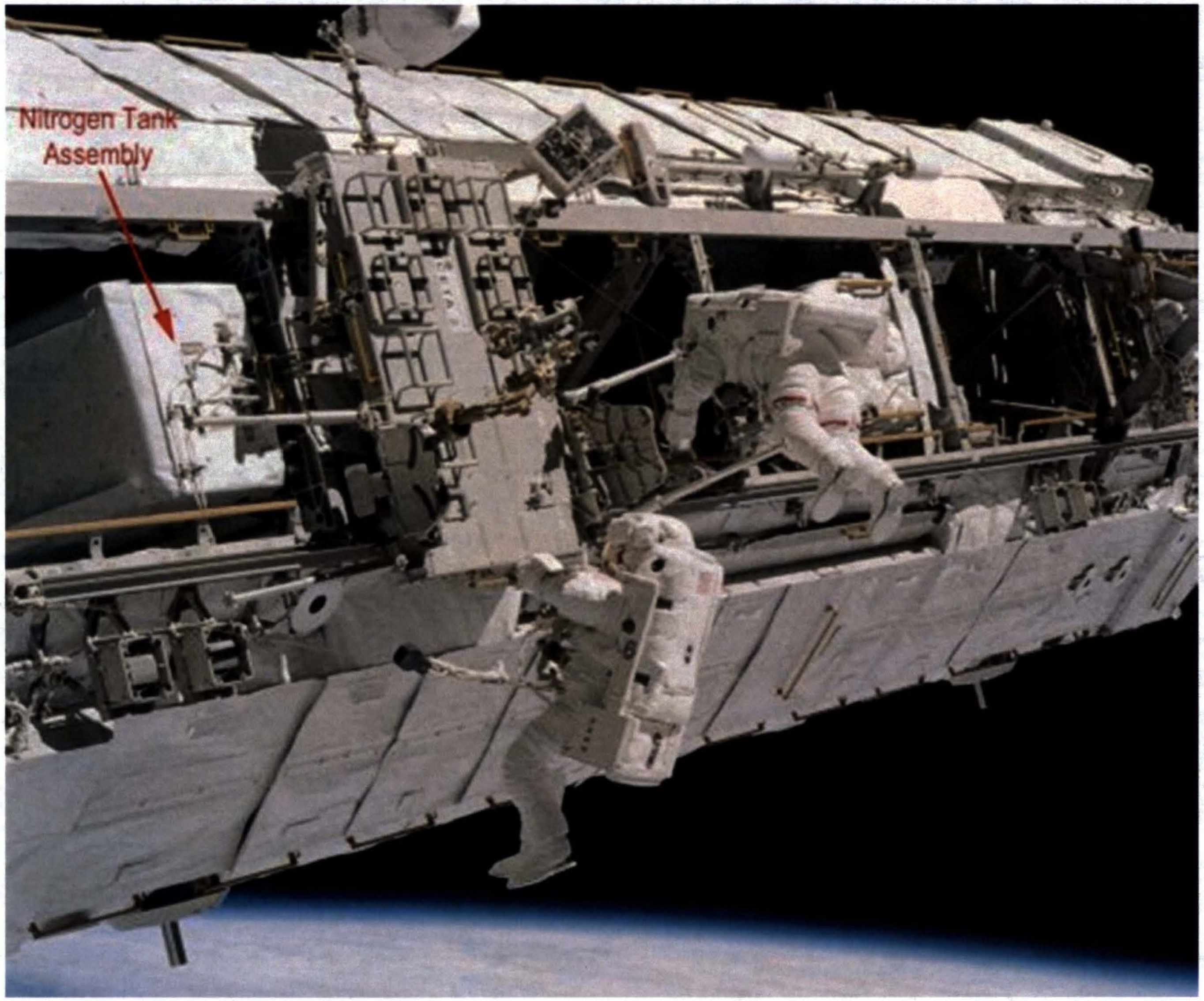
ISS Configuration ■ HPGT Locations

As of November 2009 (ULF3)



- Elements Currently on Orbit
- Elements Pending US Shuttle Launch
- Elements Pending Russian Launch

Nitrogen Tank Assembly



ISS COPV Ground Processing Risk Reduction

- Risk Reduction for ISS COPV ground processing was accomplished through multiple steps:
  - Revised mission processing operations to minimize pressurized COPV exposure time
  - ISS COPV Tracking Matrix
  - Generate ISS COPV Mechanical Damage Control Plans to control impact damage
  - ISS COPV Blast/fragmentation Damage Analysis by WSTF
  - Personnel COPV Risk Education and Imposing Access Restrictions for Pressurized COPVs in the SSPF and Pad based on the COPV blast analysis
  - Adherence to KNPR 8715.3 Safety requirements for ground processing of COPVs
  - Followed the guidelines in ES4-09-031 NASA Carbon Overwrapped Pressure Vessel (COPV) Pressure Restrictions
    - Maintain the operating strain in the fiber below 50 % of ultimate fiber strain during ground pressurization, integration and flight operations.
    - Pressurize the COPV as late in the flow as possible to minimize ground personnel exposure time.
    - Label the COPVs to prevent damage, report any inadvertent damage, maintain safety clears around pressurized COPVs (above 1/3 design burst) based on blast/fragmentation analysis.

COPV Tracking Matrix

- To better understand and assess the safety risk of processing the various ISS COPVs, KSC Safety developed the ISS COPV Tracking Matrix .
  - It contains data on each ISS COPV at KSC such as COPV liner material, fiber, resin, fill pressure, MDP, minimum design burst, volume, max fill/burst pressure, dimensions, associated mission, last fill date, MDCP hyperlink, TNT equivalent, restricted access radius, etc.
- Data in the ISS COPV Tracking Matrix was used for risk assessments and as a decision making tool.

ISS COPV Mechanical Damage Control Plans

- To address the COPV impact damage failure mode, Mechanical Damage Control Plans were written and implemented for all ISS COPVs.
- The NASA Fracture Control Board Chairman issued a COPV Damage Control Plan template document to supplement the requirements in ANSI/AIAA S-081 and KNPR 8715.3.
- ISS COPV Mechanical Damage Control Plans established procedures to prevent impact damage to COPVs during manufacturing, shipping, KSC processing and handling, and installation into ISS systems.
- ISS COPV Mechanical Damage Control Plans are now reviewed and approved as part of the ISS Ground Safety Review Panel process and by the NASA Pressure Vessel & Fracture Control Technical Monitor.

COPV Inspection at KSC

- Per KNPR 8715.3 section 13.18.1 GRAPHITE/EPOXY (Gr/Ep)COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPVs)

  c. Prior to the first pressurization of Gr/Ep COPVs at the KSC, CCAFS, VAFB or Dryden, an inspection of the vessel for visible damage shall be performed by a trained inspector.

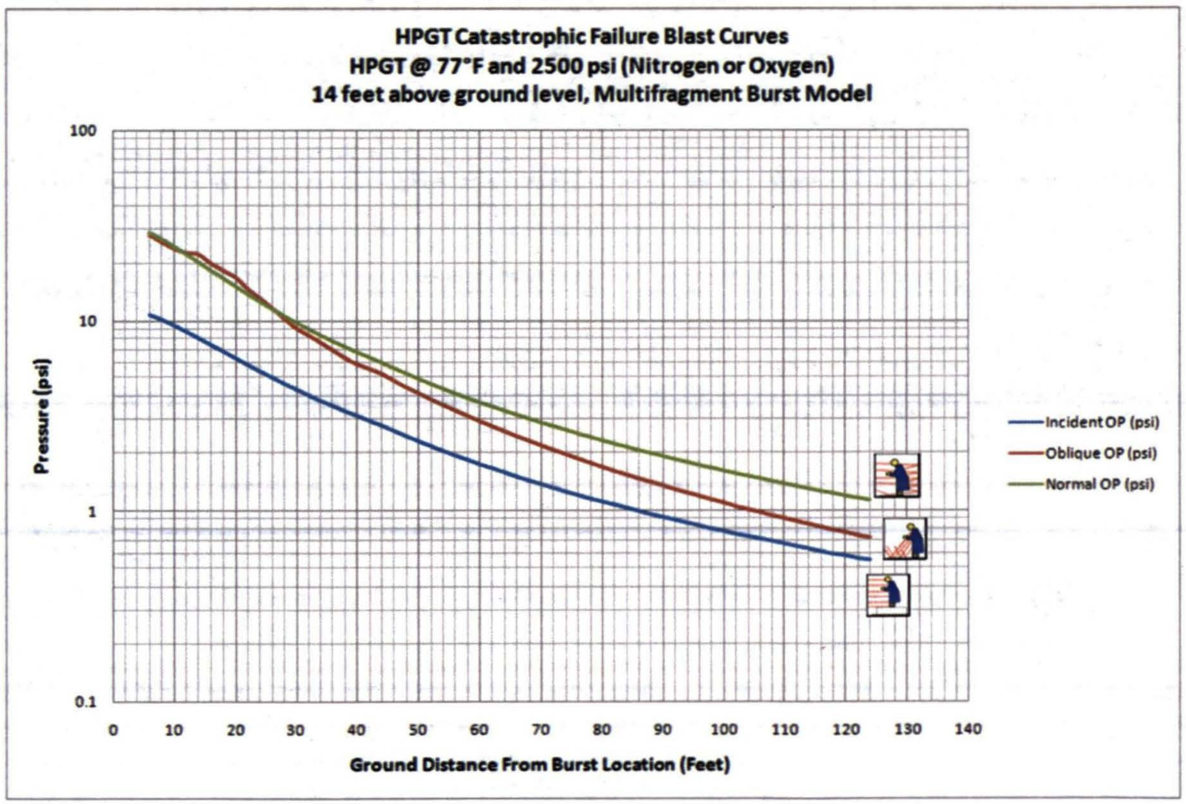
  Trained Inspector: (COPV) A person trained specifically in the detection of visual damage of COPVs and familiarized with the NDE methods and results that could be used to aid in the interpretation of visual damage. White Sands Test Facility typically conducts this training as part of their COPV damage control and inspection course.

- At KSC for ISS COPV processing, COPV inspection is provided by NASA QA personnel with WSTF COPV inspection training.

COPV Rupture Consequence

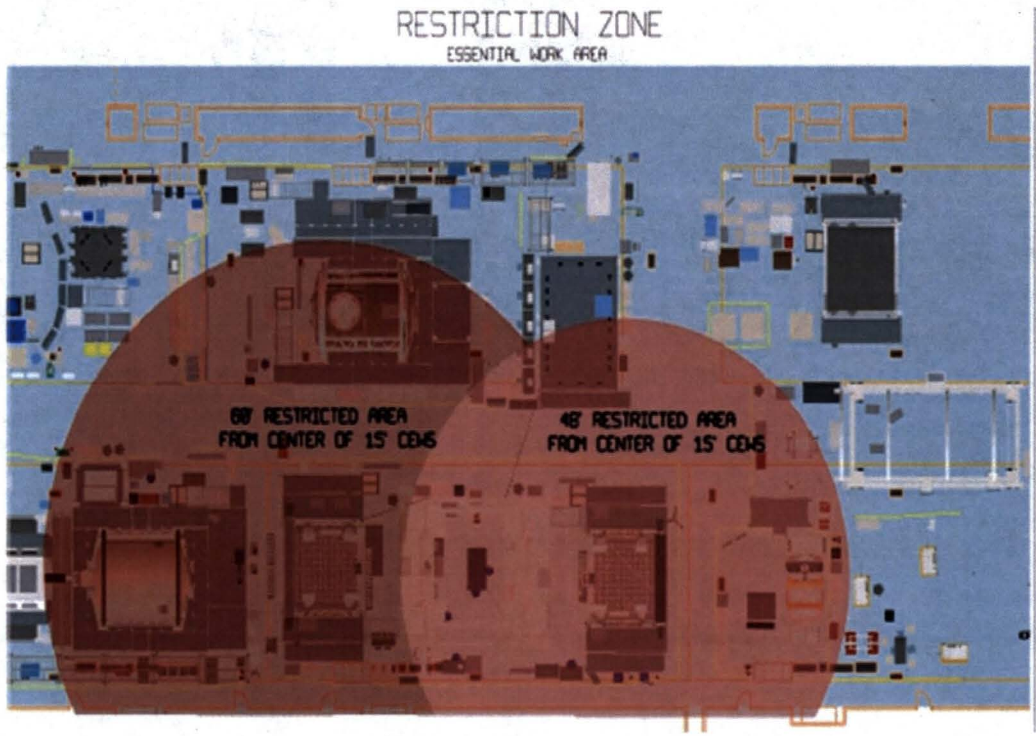
WSTF Blast/Fragmentation Analysis

- KSC assessed the COPV stress rupture consequence based on the Chris Keddy WSTF ISS COPV blast/fragmentation analysis report (Examination of Catastrophic Failure of COPVs During Ground Operations: KSC SSPF Flight ULF-3 2009)
  - Primary COPV rupture effects as well as some secondary effects were considered
- Below is a ISS COPV blast overpressure result using the PV HAZARD software



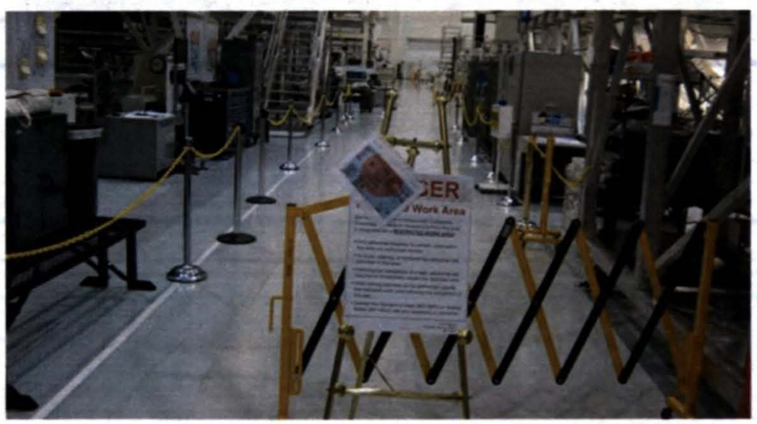
Personnel Education and Access Restrictions for Pressurized ISS COPVs

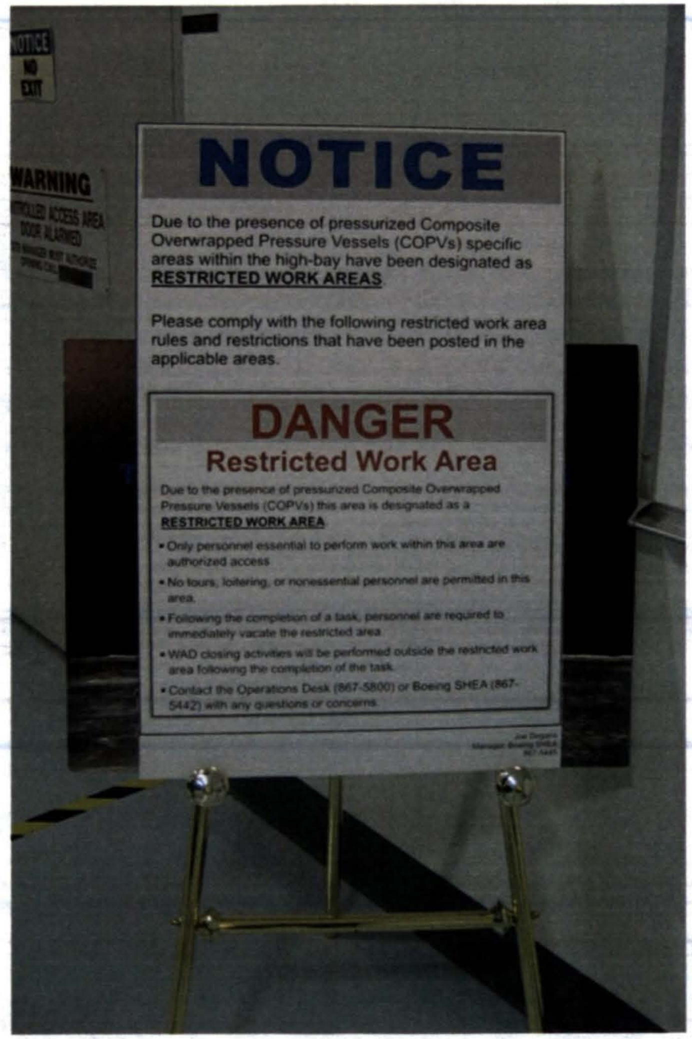
- All Space Station Processing Facility (SSPF) residents are notified of the presence of pressurized COPVs and the associated hazards.
- Personnel access restrictions around pressurized COPVs in the SSPF were based on the WSTF ISS COPV blast fragmentation analysis report overpressure curves at 3psi.
- Personnel access restricted zones in the SSPF for pressurized HPGT and NTA are shown below



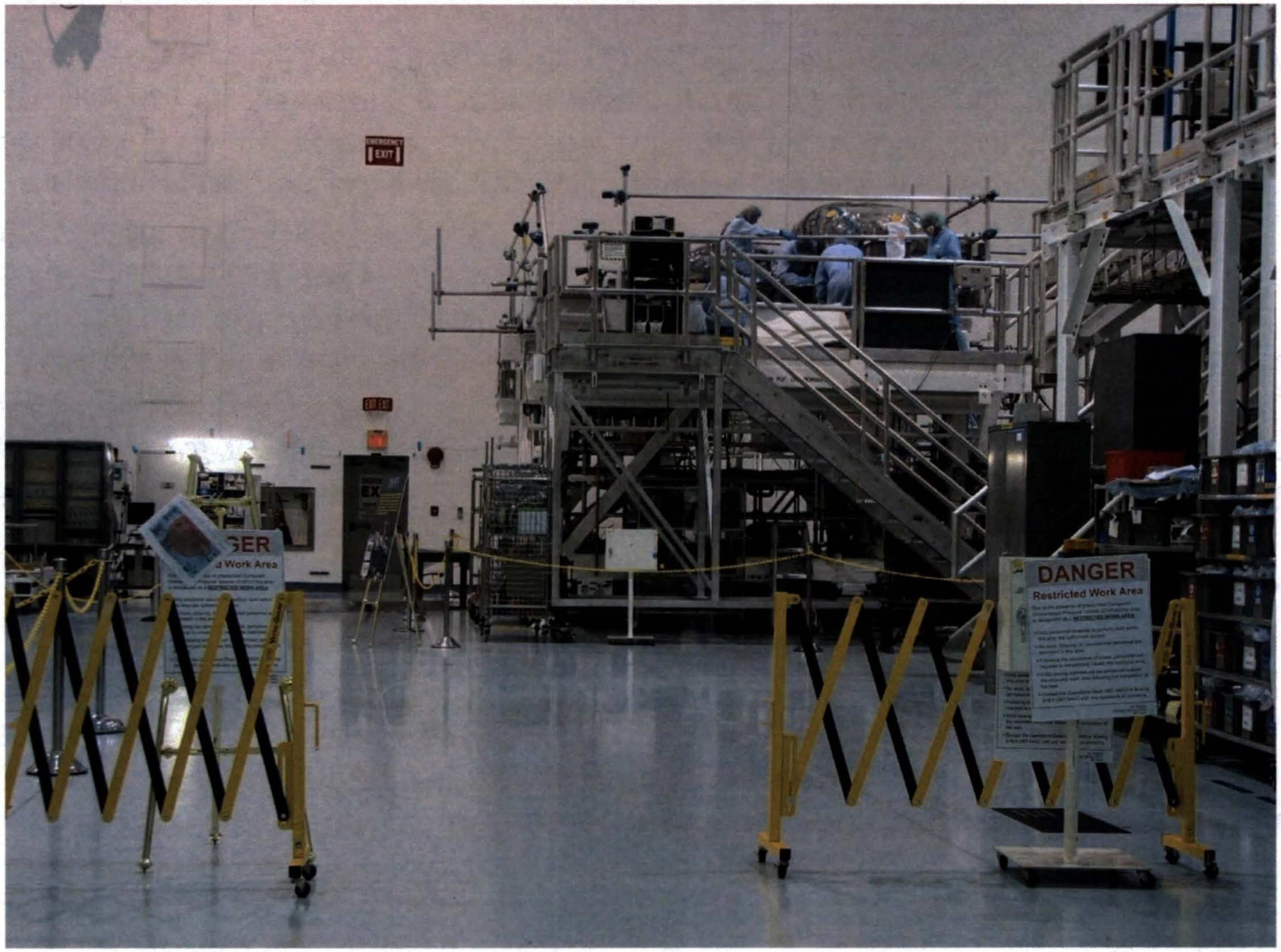
SSPF Access Restrictions around Pressurized COPVs

- COPV restricted areas in SSPF processing area with warning signage





SSPF Access Restrictions around Pressurized COPVs



KNPR 8715.3 COPV processing requirements

- **13.18 SAFETY REQUIREMENTS FOR DESIGN, TEST, AND GROUND PROCESSING OF FLIGHT COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPVS) AT THE KENNEDY SPACE CENTER (KSC), CAPE CANAVERAL AIR FORCE STATION (CCAFS), AND THE VANDENBERG AIR FORCE BASE (VAFB)**

Summarizing

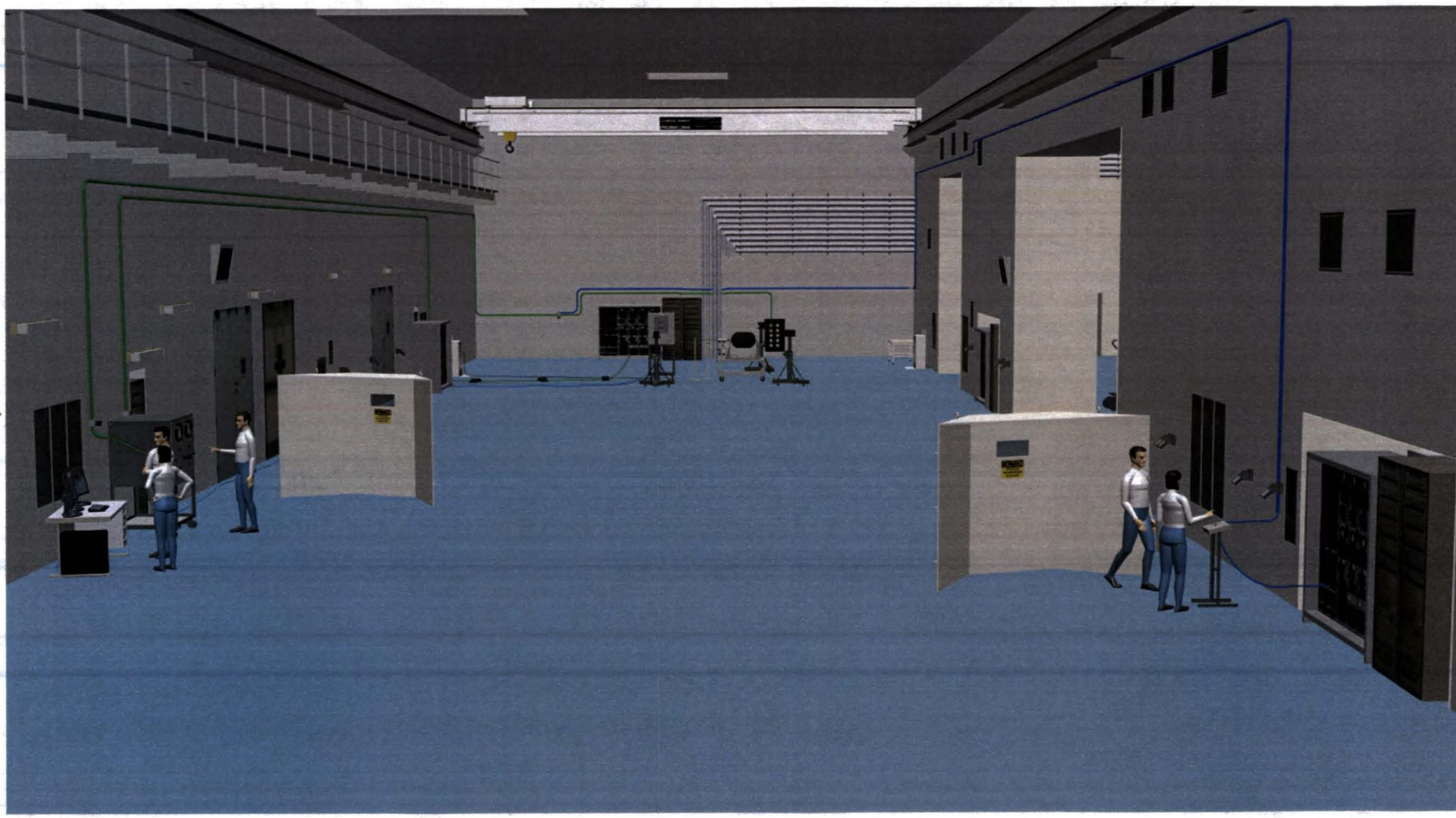
- **Prior to the first pressurization of COPVs at KSC (or last time COPV was accessible), an inspection of the vessel for visible damage shall be performed by a trained inspector.**
- **Following visual inspection, COPV shall be pressure tested to 1.1 times the ground maximum operating pressure. (If the COPV is shipped pressurized to KSC, this requirement is usually waived.). (This requirement is being considered for deletion)**
- **The 1.1 test or any pressurization above 1/3 design burst pressure shall be performed remotely or a blast shield shall be used to protect personnel**
- **Personnel limits for operations around COPVs above 1/3 design burst pressure shall be established (based on a COPV blast effects analysis).**
- **The transport of pressurized COPVs at pressures greater than 1/3 design burst pressure shall be along routes that minimize exposure to personnel and facilities with escort during designated "off-shift" time periods.**
- **A Mechanical Damage Control Plan (MDCP) for each COPV shall be provided by the design agency and made available for review by the Ground Safety Review Panel, the NASA Pressure Vessel Technical Monitor, and the KSC ISS operations and engineering department prior to operations.**

Future ISS Program COPVs

Nitrogen Oxygen Recharge System (NORS)

- **35-150 NORS COPVs will be pressurized and processed for launch on multiple ISS resupply vehicles to resupply oxygen and nitrogen to ISS for**
  - Crew metabolic needs & emergency medical usage
  - Extravehicular Activity (EVA)
  - Maintaining normal atmospheric pressure
  - Contingency module repressurization
  - Payload usage
  - Thermal Control System
- **The NORS baseline is:**
  - **COPV design to meet ISO/DOT requirements with a FOS of 3.4**
  - **DOT Special Permit to allow shipping fully pressurized COPVs from KSC to launch sites (CCAFS, Wallops, and Tanegashima)**
  - **Pressurization to flight pressures at KSC**
  - **NORS to be launched on SPACEX, Orbital Cygnus, and HTV**
  - **NORS COPV Mechanical Damage Control plan has been developed as part of the COPV design process**

NORS COPV Pressurization at KSC



Standards with Requirements for Flight Pressure Vessels

- **AIAA S-080 Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components**
- **ANSI/AIAA S-081 Space Systems – Composite Overwrapped Pressure Vessels (COPVs)**
- **Proposed Draft AIAA- S-082 –Composite Pressure Vessels (no liner)**
- **Draft BSR/AIAA S-089 American National Standard Space Systems – Composite Pressurized Structure (CPS)**
- **Note we are proposing adding ground processing requirements to the above AIAA standards, which will be discussed at the AIAA working group meeting.**
- **The KSC Safety Practices Procedural Requirements KNPR 8715.3 COPV ground processing requirements section will be revised to address the 4 types of flight pressure vessels listed above.**
- ***AIR FORCE SPACE COMMAND MANUAL (*AFSPCMAN) 91-710, Range Safety User Requirements**
- **NASA-STD 8719.24 NASA EXPENDABLE LAUNCH VEHICLE PAYLOAD SAFETY REQUIREMENTS**

Summary

- COPVs are used in NASA and Air Force spaceflight programs .
- All COPV failure modes/ Hazard causes should be addressed in the associated COPV safety analysis with recommended mitigations and controls.
- The Shuttle Program addressed the risks associated with COPVs and put practical mitigations in place to significantly reduce the ground risk.
- The ISS Program assessed COPV ground processing risks and KSC has implemented procedures to reduce ground processing risk in accordance with the NASA guidelines.
- Ground processing safety requirements for all types of Composite Pressure Vessels should be incorporated in NASA and industry standards. (This topic will be discussed in the AIAA working Group meeting later this week)

Backup

Definition of BLEVE

- BLEVE definition from Wikipedia, the free encyclopedia
- BLEVE (pronounced /*BLEV-ee*), is an acronym for Boiling Liquid Expanding Vapor Explosion.
- Mechanism
  - If a vessel partly filled with liquid with vapor above filling the remainder of the container, is ruptured, the vapor portion may rapidly leak, lowering the pressure inside the container. This sudden drop in pressure inside the container causes violent boiling of the liquid, which rapidly liberates large amounts of vapor. The pressure of this vapor can be extremely high, causing a significant wave of overpressure (an explosion) which may completely destroy the storage vessel and project fragments over the surrounding area.

Definition of Stress Rupture

- Dr. Leigh Phoenix / Cornell University provided this definition of COPV stress rupture
- Stress rupture is a sudden failure mode for Composite Overwrapped Pressure Vessels (COPVs) that can occur at normal operating pressures and temperatures. This failure mode can occur while at stress levels below ultimate strength for extended time. The failure mechanism is complex, not well understood, and is difficult to accurately predict or detect prior to failure. The location and mechanism of triggering damage causing sudden failure is highly localized, but at a random location. This location and extent of local damage has not been able to be detected by current Nondestructive Evaluation (NDE) techniques prior to catastrophic failure. Pressure, duration of time at pressure, and temperature experienced contribute to the degradation of the fiber and/or the fiber-matrix interface, particularly around accumulations of fiber breaks, and these increase the probability of COPV stress rupture.