Composite Overwrapped Pressure Vessels (COPV): Flight Rationale for the Space Shuttle Program

Introducing composite vessels into the Space Shuttle Program represented a significant technical achievement. Each Orbiter vehicle contains 24 (nominally) Kevlar tanks for storage of pressurized helium (for propulsion) and nitrogen (for life support). The use of composite cylinders saved 752 pounds per Orbiter vehicle compared with all-metal tanks. The weight savings is significant considering each Shuttle flight can deliver 54,000 pounds of payload to the International Space Station.

In the wake of the Columbia accident and the ensuing Return to Flight activities, the Space Shuttle Program, in 2005, re-examined COPV hardware certification. Incorporating COPV data that had been generated over the last 30 years and recognizing differences between initial Shuttle Program requirements and current operation, a new failure mode was identified, as composite stress rupture was deemed credible. The Orbiter Project undertook a comprehensive investigation to quantify and mitigate this risk. First, the engineering team considered and later deemed as unfeasible the option to replace existing all flight tanks. Second, operational improvements to flight procedures were instituted to reduce the flight risk and the danger to personnel. Third, an Orbiter reliability model was developed to quantify flight risk.

Laser profilometry inspection of several flight COPVs identified deep (up to 20 mil) depressions on the tank interior. A comprehensive analysis was performed and it confirmed that these observed depressions were far less than the criterion which was established as necessary to lead to liner buckling. Existing fleet vessels were exonerated from this failure mechanism.

Because full validation of the Orbiter Reliability Model was not possible given limited hardware resources, an Accelerated Stress Rupture Test of a flown flight vessel was performed to provide increased confidence. A Bayesian statistical approach was developed to evaluate possible test results with respect to the model credibility and thus flight rationale for continued operation of the Space Shuttle with existing flight hardware.

A non-destructive evaluation (NDE) technique utilizing Raman Spectroscopy was developed to directly measure the overwrap residual stress state. Preliminary results provide optimistic results that patterns of fluctuation in fiber elastic strains over the outside vessel surface could be directly correlated with increased fiber stress ratios and thus reduced reliability.
Bio:

Michael Kezirian, PhD is a systems engineer for the Boeing Company. Since 2005, he has supported the Space Shuttle and Space Station Programs in Houston, Texas. For the Orbiter Project (Shuttle) he is the Endeavour (OV-105) vehicle safety lead; in that capacity he develops safety products for the Certification of Flight Readiness and during flight represents safety activities to Boeing and NASA Program Management. Additionally, he has led the analysis team for the Orbiter COPV working group, understanding and mitigating flight risk for continued operations of the Shuttle Program. For the Space Station Program, he is a lead design engineer for the COPV development on the Nitrogen Oxygen Recharge System (NORS).

Since 1997, he has served on the faculty of the University of Southern California. As a Lecturer and now Adjunct Associate Professor, he has taught undergraduate and graduate classes in Polymer Science and the undergraduate course in Spacecraft Dynamics. He is developing a small research group developing technology for space applications.

In 2009, Dr. Kezirian was elected an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA) and, at NASA, was awarded the Astronauts’ Personal Achievement Award (Silver Snoopy).
Composite Overwrapped Pressure Vessels (COPV): Developing Flight Rationale for the Space Shuttle Program

November 3, 2010

Michael Kezirian, PhD
The Boeing Company
University of Southern California
Challenger and Columbia: Context of Safety

Challenger Disaster led to the Implementation of the Philosophy of the ‘First Law of Safety’: *The design and its operations must be proven to be safe - it is not the system safety engineer’s task to prove that it is unsafe.*

COPV Investigation represents a NASA success in understanding challenging and complex technical issues and successfully mitigating risk.
Acknowledgements (COPV Team Members)

**NASA (JSC):**
- Howard Flynn
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- Woodrow Woodworth

**NASA (GRC):**
- John Thesken
- Pappu Murthy
- Jeff Eldridge

**NASA (WSTF):**
- Nate Green
- Tommy Yoder

and many others...
Outline

- Original Shuttle Program Design & Operating Requirements
- Original Safety Considerations
- Concerns Raised During ‘Return to Flight (2005)’ after Columbia Accident
- Tank Replacement
- Operational Improvements
- Orbiter Reliability Model
  - Stress-Rupture Life of Kevlar Fiber
  - Stress Ratio Model-Orbiter Tanks
  - Temperature Dependence
  - Accounting for Material Variability and Data Uncertainty
- Recent Discovery of Titanium Liner Ripples on Vessel Interior
  - Analysis of Potential Buckling
- Validating Reliability Model
  - Accelerated Stress Rupture Test
  - Bayesian Analysis – how to incorporate new information
  - Raman Spectroscopy measurement of current fiber stresses
- Future for Composite Vessels at NASA
  - International Space Station
  - NORS
  - Commercial Satellites
  - Future Exploration
- Aging Concerns for Kevlar and Carbon COPV
  - Material Degradation and Radiation effects on Lifetime
Orbiter COPV Configuration

Main Propulsion System (MPS)
- Three 40” He
- Seven 26” He

Orbital Maneuvering System (OMS)
- Two 40” He

Reaction Control System (RCS)
- Two 19” He (each)
  - Left, Right and Forward

Environmental Control and Life Support System (ECLSS)
- Four to Six 26” N₂

Location of Orbiter Fluid Tanks

- Titanium liner (0.104” thick) and boss.
- Overwrap: Kevlar-49 fibers in Epoxy (0.739” thick)
  Composite carries ~ 70-80% of load
  (at operating pressure)
COPV Weight Savings

- 24 Kevlar COPVs saved approximately 752 pounds per Orbiter Vehicle (compared to an all metal tank design)

- Orbiter Dry Weight
  - 176,056 pounds (Endeavour)
  - 176,419 pounds (Discovery)
  - 176,413 pounds (Atlantis)

- Payload Capability
  - 54,000 pounds* (28.5 deg Orbit)
  - 36,200 pounds* (51.6 deg Orbit)

*including manager’s reserve, payload attach hardware and flight support equipment
Original Design Criteria

- **Original requirements:** 100 mission in 10 years
  - 1988: Life certification extended to 20 years
- **Primary Failure Mechanism Considered:** Liner Failure (parent material or weld)
- **Led to Design Requirement:** Leak Before Burst (LBB)
  - Liner Failure Mechanism:
    - Imposed: when the liner fails (parent material or weld) a pinhole develops such that the pressurized gasses would slowly leak through the overwrap, but the liner would remain sufficiently intact such that a more sudden unzipping or explosive burst failure would not occur
    - Noted: However, sudden liner unzipping did in fact occur during several proof tests.
  - Fail Operational, Fail Safe:
    - If one tank were lost, Shuttle Program could continue its mission
    - If two tanks were lost, Orbiter could return home safely
      - Failure of 2 40” MPS tanks – Intact abort
      - Failure of 2 40” OMS tanks – Blowdown mode, sufficient propellant for deorbit burn
      - Failure of 2 ECLSS, 26” MPS or RCS tanks – System redundancy mitigated catastrophic failure for loss of gas
    - Accounted for risk of overpressurization of the vehicle and effect on structural integrity
- **Verification:** Leak Before Burst (LBB)
  - 20 Tanks were tested (artificially fatigued with induced flaws in order to fail in the liner).
  - Experiments confirmed LBB failure mechanism.
- Composite Stress Rupture was mitigated by design; the maximum burst pressure was selected such that the stress in the fibers was believed low enough to preclude failure in the life of the program.
Original Design Criteria: Composite Stress Rupture

Original certification of Orbiter tanks was based on 2 sets of data:

- JSC fleet leader test program – 25 vessels (very little time accumulated at that point)
  - Intended to envelop fleet tanks in both stress ratio and time
- Statistical reliability models based on Lawrence Livermore National Lab (LLNL) epoxy-impregnated strand and vessel tests (only a few thousand hours accumulated; strand data problematic)
  - LLNL tests had small 4.5” dia tanks with low strength but thick (same as overwrap) Aluminum liners, pressurized to 50-86% of ultimate fiber stress

- Subsequent data (up to 100,000 hrs) and refined analysis methodology, as well as revised stress-ratio calculation by COPV Team (based on actual burst strengths) concluded that risk of stress rupture was much higher than original predictions
  - Led to realization fleet leader program not be enveloping stresses of all fleet tanks

- Recognized differences exist between LLNL, fleet leader and flight tanks but LLNL data is the only statistically large sample of data available
  - Identified follow-on effort to establish conservatism of LLNL based predictions for Shuttle tanks

<table>
<thead>
<tr>
<th></th>
<th>LLNL Vessels</th>
<th>Fleet Leaders</th>
<th>Fleet Vessels</th>
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<tr>
<td>Diameter (in)</td>
<td>4.5</td>
<td>10.4</td>
<td>19 - 40</td>
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<tr>
<td>Liner Material</td>
<td>1100 Al</td>
<td>5086 Al</td>
<td>Ti-6Al-4V</td>
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<tr>
<td>Liner Thickness (in)</td>
<td>0.04</td>
<td>0.04</td>
<td>0.044 (RCS He)- 0.104 (OMS He)</td>
</tr>
<tr>
<td>Overwrap Thickness (in)</td>
<td>0.04</td>
<td>0.25</td>
<td>0.285 (RCS He)- 0.739 (OMS He)</td>
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<td>Overwrap Pattern</td>
<td>delta axi-symmetric</td>
<td>Complex</td>
<td>Complex</td>
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<tr>
<td>Resin</td>
<td>DER 332/Jeffamine T403</td>
<td>LRF-092</td>
<td>LRF-092</td>
</tr>
<tr>
<td>Fiber</td>
<td>Kevlar 49 - 380 Denier</td>
<td>Kevlar 49 - Type 969</td>
<td>Kevlar 49 - Type 969</td>
</tr>
<tr>
<td>Quality Control</td>
<td>Little, if any</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td># Build Spools</td>
<td>One</td>
<td>Multiple</td>
<td>Multiple</td>
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<tr>
<td>Pre-test Load</td>
<td>None</td>
<td>Proof test</td>
<td>Proof test</td>
</tr>
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</table>
Return to Flight: COPV Safety Reconsidered

- Revisit of Orbiter COPV Design
  - Re-examination of original Lifetime Certification data, Qualification Test Reports and Vessel Data Packages resulted in new concerns
  - Calculated probability of having a failure after 113 flights: 0.20
    - Too high to accept the risk; not too high to discredit risk
  - Composite stress rupture failure equivalent to explosive energy of 14 lbs of TNT
  - Shuttle Program: 30-40 missions (per vehicle) in 30 years
    (compares with Original requirements: 100 mission in 10 years and 1988 re-certification to 20 years)

- Orbiter Engineering Team Tasked:
  1. Investigate tank replacement/procurement new COPV
  2. Make Improvements to Shuttle operations to reduce effective time at pressure
  3. Develop an Orbiter reliability model to quantify future risk based on more recent recent test data and analysis of past data
### COPV Risk Relative to Top Shuttle Program Risks (Iteration 3.1)

<table>
<thead>
<tr>
<th>Rank</th>
<th>% of Total</th>
<th>Cumulative Total</th>
<th>Probability (1/n)</th>
<th>Failure Group</th>
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<tbody>
<tr>
<td>1</td>
<td>30.9</td>
<td>30.9</td>
<td>3.6E-03 (1 in 277)</td>
<td>Micrometeoroids and Orbital Debris (MMOD) strikes Orbiter on orbit leading to Loss of Crew or Vehicle (LOCV) on orbit or entry</td>
</tr>
<tr>
<td>2</td>
<td>13.2</td>
<td>44.1</td>
<td>1.5E-03 (1 in 652)</td>
<td>Space Shuttle Main Engine (SSME)-induced SSME catastrophic failure</td>
</tr>
<tr>
<td>3</td>
<td>10.2</td>
<td>54.3</td>
<td>1.2E-03 (1 in 840)</td>
<td>Ascent debris strikes Orbiter Thermal Protection System (TPS) leading to LOCV on orbit or entry</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>61.3</td>
<td>8.2E-04 (1 in 1,220)</td>
<td>Crew error during entry</td>
</tr>
<tr>
<td>5</td>
<td>5.6</td>
<td>66.9</td>
<td>6.5E-04 (1 in 1,530)</td>
<td>Reusable Solid Rocket Motors (RSRM) - induced RSRM catastrophic failure</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>68.5</td>
<td>1.8E-04 (1 in 5,510)</td>
<td>Common cause failure of the Electrical Power System on orbit</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>70.0</td>
<td>1.7E-04 (1 in 5,890)</td>
<td>Solid Rocket Booster (SRB) Auxiliary Power Unit (APU) shaft seal fracture</td>
</tr>
<tr>
<td>8</td>
<td>1.3</td>
<td>71.3</td>
<td>1.5E-04 (1 in 6,480)</td>
<td>SRB booster separation motor debris strikes Orbiter windows</td>
</tr>
<tr>
<td>9</td>
<td>1.3</td>
<td>72.6</td>
<td>1.5E-04 (1 in 6,640)</td>
<td>An existing crack in the Orbiter APU turbine wheel propagates resulting in catastrophic failure of the APU during entry</td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
<td>73.8</td>
<td>1.4E-04 (1 in 7,350)</td>
<td>Common cause failure of the APU System on entry</td>
</tr>
</tbody>
</table>
COPV Tank Replacement

Investigated Hardware Modification Option to replace existing COPVs

Certified procedures exist for replacement of MPS and ECLSS tanks. Consider feasibility to replace existing OMS/RCS tanks.

Presented by: W. F. Rogers
10/05/2005
## Margin Improvement Options
### (OMS/RCS COPV Replacement)

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Margin Post Implementation</th>
<th>Relative Complexity</th>
<th>Risks</th>
<th>Schedule: Hardware On Dock</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Replace Existing Tanks with new drop-in MC282-0082-XXXX replacements</td>
<td>Acceptable</td>
<td>Low: • New Tank • OMS 40&quot; Tank Replacement</td>
<td>Medium: • Tank procurement schedule • OMS Pod skin damage</td>
<td>18 months</td>
<td>Medium</td>
</tr>
<tr>
<td>1B</td>
<td>Replace Existing Tanks with nearest COTS equivalent</td>
<td>Acceptable</td>
<td>High: • Requires extensive redesign of OMS Pod structure and/or helium system</td>
<td>High: • Nearest COTS tank that meets minimum OMS helium quantity requirements is a cylindrical tank substantially larger than the existing tank; would require complete redesign, remanufacture, and recertification of the OMS Pods</td>
<td>24 - 36 months</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>Swap OMS 40&quot; tanks with MPS 40&quot; tanks</td>
<td>UNACCEPTABLE Minimal improvement</td>
<td>Low: • 40&quot; OMS Tank Replacement • 40&quot; MPS Tank Replacement</td>
<td>Medium: • OMS Pod skin damage • Aft compartment damage</td>
<td>0 months</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>Add an additional tank or tanks to increase OMS system volume to reduce pressure</td>
<td>Acceptable for OMS; Not Applicable to RCS</td>
<td>High: • New plumbing/tank mounting provisions in aft • New instrumentation (temp sensors) • New interface (Aft/OMS) • Recert of OMS system etc. • 26&quot; tank procurement</td>
<td>High: • System design • Tank procurement schedule • Addition of new failure modes • Damage in Aft Compartment during mod • RCS tank margins</td>
<td>14 - 18 months (assumes use of 2 tanks from Logistics inventory)</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>Strengthen existing tanks by adding additional layers of overwrap</td>
<td>Unknown</td>
<td>High: • Requires extensive development, analysis, and qualification effort</td>
<td>High: • Margin improvement may not be quantifiable • Many technical unknowns (low technical maturity - TMM Level 2) • Likely requires new procurement to replace devel/qual tanks</td>
<td>14 - 18 months</td>
<td>Medium-High</td>
</tr>
</tbody>
</table>
## OMS Tank Removal Replacement Feasibility

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Feasibility</th>
<th>Relative Complexity</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remove RCS stinger and extract tank out end of Pod</td>
<td>Feasible</td>
<td>High:</td>
<td>Medium:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Requires cutting 10 RCS prop. lines</td>
<td>• RCS system damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Thrusters must be refurbished</td>
<td>• Stinger structural reattachment</td>
</tr>
<tr>
<td>2</td>
<td>Remove OMS NTO tank and extract He tank out opening</td>
<td>Not Feasible</td>
<td>High:</td>
<td>High:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Bulkhead opening is too small</td>
<td>• OMS Pod modification would be extensive</td>
</tr>
<tr>
<td>3</td>
<td>Remove Pod aft outboard skin and extract tank out opening</td>
<td>Feasible</td>
<td>Medium:</td>
<td>Medium:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Requires removal of 180 HiLoks</td>
<td>• OMS Pod skin damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Requires removal of NTO tank</td>
<td></td>
</tr>
</tbody>
</table>

### Identified Risks:
- Composite honeycomb OMS Pod skin damage during HiLok removal
  - Determined accessibility of HiLok collars – 99% accessible if NTO tank is removed first
  - Identified skin repair procedures
    - Edge distance is sufficient to over-size holes
  - Began discussions with WSTF for a trial-run on the Fleet Leader OMS Pod
    - WSTF fleet leader helium tanks may be used for COPV testing, forcing removal anyway
- Initiated Structural Model To Assess Pod Rotation With Skin Removed
- Identified GSE and Developed Concepts
  - Skin handling strongback
- Initiated Preliminary Implementation Plans
OMS and MPS tanks (identical parts) were deemed the highest risk to the program.

- Two flight spares were used to replace the two MPS vessels, COPVs with lowest estimated reliability (SN 006 and 007).
- SN 006 was designated as a flight spare
- SN 007 was later ‘sacrificed’ for the Accelerated Stress Rupture Test.
- Main cause (now recognized in hindsight) was the low burst strength performance of these 40 in. diameter vessels compared to others, especially 26 in. MPS vessels (virtually scale models)
  - Burst strength fell short by about up 15% of that reasonably expected
Mitigation: Changes implemented to reduce flight risk

- **Two stage load**
  - Loading procedure is split into two steps, first to 80% then to designated flight pressure$. The temperature rise during loading corresponds to the fastest accrual of effective hours; the two step process allows the tanks to dissipate this heat in order to minimize the effect of the overshoot.

- **Pressurization improvements**
  - Fill requirements are set to specified temperature limits and precise tank fill level rather than minimum level.

- **System Checkout**
  - Tests performed at 80% of operational value instead of 100%.

- **Reduced time at load**
  - Servicing (loading flight gasses) occurs later in the launch countdown cycle; OMS tank loads moved to 4 days prior to launch (previously as early as 12 days).

- **Pad Clears**
  - Ground personnel are prohibited near the vehicle while tanking, which is the highest risk procedure

- **Restricted Pad Access**
  - Restrict pad access to essential personnel only after pressurization of COPVs

- **OMS offload**
  - Reduce He pressure on the OMS tanks, reducing the corresponding stress loads

$Temperatures in the past had gone to 180°F (82°C) or higher
Typical MPS Load Profile

Pressure (psia)

Mid Temperature (F)

Aft Temperature (F)

<table>
<thead>
<tr>
<th>Name</th>
<th>Nomenclature</th>
<th>Units</th>
<th>Data Source</th>
<th>Date</th>
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<th>HI</th>
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<tr>
<td>V41T1109C1</td>
<td>MPS E1 SUPPLY BOTTLE PRESSURE</td>
<td></td>
<td></td>
<td></td>
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<td>V41T1110A1</td>
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<td>072505</td>
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<td>072505</td>
<td>78</td>
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</tbody>
</table>
Two-Stage Loading Process

Introducing a “Cheat Load”, greatly reduces the time at elevated temperature and pressure.
### Operational Improvements Summary

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>#</th>
<th>Old Load</th>
<th>New Load</th>
<th>Cheat Load</th>
<th>Temp Limits (deg F)</th>
<th>Original Effective Hours</th>
<th>Effective Hours (2 day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMS (Full Load)</td>
<td>2</td>
<td>T-12</td>
<td>T-6</td>
<td>Y</td>
<td>100</td>
<td>200</td>
<td>105</td>
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<td>N</td>
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Launch Scrubs and Weather conditions affect actual accrued time.
OMS Offload

- Reduce helium pressure on the OMS tanks, reducing the corresponding stress loads
- Pressure in the helium tanks is driven by the failure scenario of a launch abort (Return To Launch Site-RTLS). In this scenario, it is necessary to expel the liquid fuels in the OMS liquid propellant tanks in order that the Orbiter vehicle will meet landing center of mass constraints.
- Reducing the OMS liquid fuel and corresponding helium pressure meets RTLS constraints and only loses 10 pounds Ascent Performance Margin (APM).
- OMS COPV pressure is reduced from 4875 psia to 4450 psia.
- New Helium pressure reduces effective accumulated time from 105 hrs to 35 hrs, reducing stress rupture risk by a factor of 3.
# Evaluation of Accumulated Hours

<table>
<thead>
<tr>
<th>Flight</th>
<th>Vehicle</th>
<th>Date</th>
<th>OMS (L &amp; R)</th>
<th>MPS (L, R &amp; C)</th>
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<td><strong>Projected Hours</strong></td>
<td><strong>Standard OMS</strong></td>
<td><strong>Full OMS Load</strong></td>
<td><strong>35 hrs/flight</strong></td>
<td><strong>90 hrs/flight</strong></td>
</tr>
</tbody>
</table>

- STS-125 carried a Full OMS Load.
- Red indicates accumulated hours exceeding projections.
Orbiter Reliability Model Key Features:

- Understand the *actual* stress ratio of each COPV in the fleet
  Two vessels otherwise identical in design (but manufactured at different times) could have significantly different stress ratios because of measured mechanical response differences during proof testing (e.g. permanent volume growth was found to vary by up to a factor of two)

- Account for temperature variations and high excursions during pressurization and flight

- Account for actual previous time-under-load history of each COPV in the fleet through determining effective accumulated time under pressure
Kevlar Industry Database

- Revisited large body of data on strength and stress-rupture of Kevlar-49/epoxy composites used in COPVs (got LLNL to declassify and release data updates from 1981-1988)
- Applied a micromechanics based statistical model to interpret it
- Data based
  - LLNL (‘72-’88, strand and vessels *released in 2005*)
  - NASA Fleet Leader (‘78-’03)
  - Cornell single fiber tests (large replications at various temperatures, ‘82-’06)
  - duPont/DOE (‘83-’85) a repeat of LLNL vessel tests effort to resolve spool effect anomalies
- Phenomena involved: matrix volume fraction, temperature, size effect, loading rate effects, liner effects, spool-to-spool effect
- Result: Eventually obtained consistent view of stress-rupture of Kevlar-49/epoxy composites in comparing, fibers, strands and various vessel sets
Lifetime distribution function under stress history $\tilde{\sigma}(t)$, $t \geq 0$ and const. temperature,

$$F(t|\tilde{\sigma}(\cdot)) = 1 - \exp \left\{ -\frac{V}{V_{ref}} \left[ \int_0^t \left( \frac{\tilde{\sigma}(s)}{\sigma_{ref}} \right)^{\rho_1} \frac{ds}{t_{ref,1}} \right]^{\beta_1} \right. 
+ \left[ \int_0^t \left( \frac{\tilde{\sigma}(s)}{\sigma_{ref}} \right)^{\rho_2} \frac{ds}{t_{ref,2}} \right]^{\beta_2} \right\}$$

Time const., power-law exponent, Weibull life shape parameters

$t_{ref,1}, \rho_1, \beta_1$, parameters for $t >> 100$ hours

$t_{ref,2}, \rho_2, \beta_2$, parameters for $t < 100$ hours

Weibull shape parameter for strength

$$(\rho_1 + 1) \beta_1 = (\rho_2 + 2) \beta_2 = \alpha$$
Problem 1: Fiber volume fraction influences effective mean fiber strength of Kevlar/epoxy strands (after rule of mixtures calculation)
- Lifetime vs fiber stress for various Kevlar 49/epoxy strands (volume fraction effect originally confounded stress ratio concept)
Problem 2: Lifetime of Kevlar 49/epoxy strands at 0.791 fiber stress ratio showed evidence of "trunsoring" (failures on loading expected based on strength distribution) two regimes emerged when finally corrected.
Problem 3: Since 30 vessels were made from each spool (7 spools) serious spool effects emerged, so had to develop analytical technique to remove spool-to-spool effects uniformly between strength and life.
Problem 4: Anomalies in burst strength of Kevlar 49/epoxy pressure vessels (LLNL vs duPont-DOE rerun) finally resolved when spool effects and liner yield strength differences taken into account.
Problem 5: Lifetime discrepancy emerged between LLNL vessels versus virtually identical duPont/DOE replicates (as well as strands). *What went wrong? Apparently a p-T Ratchet effect.*

\[
\begin{align*}
\text{Fiber stress ratio} & = \frac{\text{Weibull lifetime scale parameter, hours}}{\text{Temperature fluctuation}} \\
\text{Weibull lifetime scale parameter, hours} & = \frac{1000}{10000} \\
\text{Temperature fluctuation} & = \frac{1000}{10000}
\end{align*}
\]
- Considerable temperature fluctuations winter to summer cause plastic liner yielding followed by “topping off” and a ratchet effect increasing the overwrap stress over time.

- Lifetime of Kevlar 49/epoxy pressure vessels with very thick 1100-0 Aluminum liners $t_K/t_{Al} \sim 1.00$ and very low yield strength (4.5 MPa).
Kevlar Industry Database

- How it looked when all the data was put together (~ 1000 data points)
- If ratchet effect were not accepted as cause of low power-law parameter, flight rationale probably not possible
Data on temperature effects finally resolved the issue $\rho \propto 1/T$ was key discriminator
Stress Ratio of Orbiter COPV

- For the existing Orbiter vessels, at operating pressure, what is the stress ratio are the Kevlar fiber?

Conside 26” Tanks:
- Three tanks were burst to determine
- For operating pressure = 4500 psi, stress ratio ~ 0.47
- Reliability estimates at these stress ratios for the existing Kevlar database gives risk less than 1:1 million (i.e. at least 6 ‘9’s’).

Consider 40” Tanks:
- Burst Pressure of SN 002: 8,010 psia
- Burst Pressure of SN 011: 7,667 psia
- Operating pressure at 4875 psia (OMS) stress ratio SR = 64%
- Operating pressure at 4500 psia (MPS) stress ratio SR = 53%
- Not acceptable reliability estimates
Tank Production History

Vessel Fiber Stress Ratio tied to performance of individual 40” Tanks based on original acceptance test data. *Permanent* growth in tank volume during initial autofrettage is key parameter. Large volume growth implies through thickness compaction, high stress gradient and thus higher stress in inside fibers driving up overall stress ratio.
Introduce Variability and Uncertainty

- Log Normal Distributions accurately represent uncertainties in estimated parameters:
  
  \[(\text{power-law, } \rho, \text{ Weibull, } \beta, t_{\text{ref}}, \text{ etc.})\]

- Definitions:
  - Point – Reliability prediction calculated based on the best-estimated values for key parameters ignoring uncertainty
  - Monte Carlo Simulations performed; key parameters ‘randomized’ with log-normal uncertainty distributions; Reliability calculated:
  - Mean – Average reliability from simulation of uncertainty (tied to size of data set).
  - 95% confidence – The 95% percentile ‘worst case’ (more or less) reliability from among the simulation set.

- Shuttle Program based flight decisions on Mean Reliability (best able to weigh deep tail uncertainty effects beyond 95% percentile) although all three presented reliability numbers calculated for various scenarios.
Incorporating Temperature Dependence

Based on the time – temperature shift and superposition relations, historic loading profiles of the Orbiter Vehicle and Operational Improvements, reliability was based on predicted future hours per flight.
Shuttle Database and Past Time

- Extensive database provides the opportunity for Engineers to calculate the historic cumulative effective time under pressure (accounting for temperature and pressure variations) of all tanks in the fleet.

- Condition Reliability calculated, Probability of Survival that for Past hours plus future hours, given that tank has already survived the specified number of past hours.

- Combining:
  - Kevlar Database for Lifetime of fibers at given stress ratios
  - Stress Ratio for each individual vessel (40” OMS and MPS)
  - Anticipated Future hours (based on Shuttle operations)
  - Monte Carlo Simulation for Mean, Point and 95% Confidence Limit
  - Presented per flight, per vehicle and overall program risk
Shuttle Database and Past Time

- **Arrhenius based model in power-law framework**
- **Convert Stress Ratio at elevated temperature to Stress Ratio at reference temperature:**

\[
S(p, T_{el}) = \Phi^{(T_{el,K} - T_{ref,K})/T_{el,K}} S(p, T_{ref})^{T_{ref,K}/T_{el,K}},
\]

\[
\Phi = 2.86, \quad T_{ref,K} = 300\,^\circ K \quad (80.6\,^\circ F), \quad \rho \equiv \rho_{ref} = 24
\]

\[
\rho_{el} = \rho T_{ref,K} / T_{el,K}
\]

- **Time-scale conversion for pressure & temperature change follows:**

\[
\tilde{t}(p_{el}, T_{el}) = \tilde{t}(p_{ref}, T_{ref}) \left[ S(p_{ref}, T_{ref}) / \Phi \right]^{\rho(1 - T_{ref}/T_{el})} \left[ S(p_{ref}, T_{ref}) / S(p_{el}, T_{ref}) \right]^{\rho(T_{ref}/T_{el})^2}
\]
Orbiter Reliability Model developed in Matlab

### OV-103 Parameters

**COPV Reliability Program Ver 2.0**

<table>
<thead>
<tr>
<th>Component</th>
<th>Stress Ratio</th>
<th>Time Past (hr)</th>
<th>Time Mission (hr)</th>
<th>Number of Tanks</th>
<th>Pfi Reliability</th>
<th>Mean Reliability</th>
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</table>

**Vehicle Reliability**

- **CN-4.03**
- **Reliability Point**: 9.999997
- **Number of Trials**: 1
- **Reliability Confidence**: 9.999994

---

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Life of Program Reliability Estimate

Two Day Launch Scrub - PRCB 10/18/2007

From STS-118

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<th>Per Flight Reliability Numbers</th>
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<th>OMS Reduced</th>
<th>OMS Full</th>
<th>OMS Reduced</th>
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<td>.999 42</td>
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<td>.999 978</td>
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Cumulative Reliability (per vehicle) From # of Flights

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<th>1 Flight</th>
<th>5 Flight</th>
<th>1 Flight</th>
<th>1 Flight</th>
<th>1 Flight</th>
<th>6 Flight</th>
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<td>0.997 3</td>
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</table>

Life of Program COPV Reliability 15 Flights Combined

\[ 0.998 64 \times 1.710 = 0.998 63 \times 1.489 \]

\[ 0.992 55 \times 1.134 \]

Life of Program, 15 flight Failure Likelihood

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

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

COPV Risk Profile - OV-103

- Personnel at Risk
- Mitigated by Clears

Stage 1
- Hold
- Load

Stage 2
- Load
- Hold

EECLS
- 2.12E-10

L-Days
- 0.00E+00 to 5.00E+00
- 10.00 to 9.00 to 8.00 to 7.00 to 6.00 to 5.00 to 4.00 to 3.00 to 2.00 to 1.00 to 0.00

Burst Risk per Hour
- 0.00E+00 to 5.00E-06
- 5.00E-06 to 4.50E-06 to 4.00E-06 to 3.50E-06 to 3.00E-06 to 2.50E-06 to 2.00E-06 to 1.50E-06 to 1.00E-06 to 0.50E-06 to 0.00E+00
## OV-103 Risk Profile

### Table Showing Risk by Subsystem

<table>
<thead>
<tr>
<th>Event</th>
<th>Timeline</th>
<th>L-Days</th>
<th>Risk Per Hour</th>
<th>Risk</th>
<th>1 in ... Risk</th>
<th>OMS</th>
<th>MPS</th>
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<td>2.06E-07</td>
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**Note:** Once the vehicle reaches Orbit, the COPV risk is gone.
Mitigating Buckling Concerns

Analysis of Potential for Titanium Liner Buckling after Proof in a Large Kevlar/Epoxy COPV, AIAA 2009-2520
During initial internal borescope inspection of 40” COPV S/N 002 at WSTF an anomalous surface condition was noted:

- Borescope inspection performed as part of health assessment – designated as potential spare for installation in OV-104

Rippled or wavy appearance observed:

- Found throughout (360° around) the membrane regions (both halves)
- Suspect that condition may be result of liner buckling

Possible impacts of liner buckling:

- Reduction in fatigue life
- Change in load sharing properties between liner and overwrap
- Change in reliability
Borescope Photographs
Experimentally Observed Surface Depressions

Cross-Section of Surface Depressions

26 in. tank

Circumferential degrees around equator

Meridional degrees from equator

22 mil depth

40 in. tank

Circumferential degrees around equator

Meridional degrees from equator

Cross-hatch ripples are approximately 0.003° in amplitude.

Max deflection = 0.020°
Modeling Steps

**Step 1: Pressurization up to proof pressure**
- Model liner yielding, formation of local valleys from void compaction
- Characteristic shapes compared to measurements.
- Calculate liner properties.

**Step 2: Depressurization to zero pressure**
- Calculate growth of Step 1 deformation.
- Frozen in pressure and moment distributions from Step 1 become “forcing functions” in Step 2, driving increased transverse displacements, potentially leading to buckling.
- During unloading we track transverse displacements, bending moments, and through-thickness liner stress profiles to compare to lowered compressive yield thresholds from the Bauschinger effect.

**Step 3: Assembling the results**
- Finally we put it all together and assemble the results for the various stages up to peak proof pressure and the subsequent depressurization to zero vessel pressure.
- We mention the criteria that allow final assessment of the likelihood of liner buckling for various values of initial ‘frozen-in” depression depths as seen in profilometry inspection.
Bauschinger Effect from Yielding

Material response in tension differs than in compression. Bauschinger effect becomes key in developing instability wherein extensive prior yielding in tension reduces the magnitude of the yield threshold in compression by 30 to 40% compared to the virgin annealed state of the titanium.
Effect of Reducing Liner Stiffness by 15% on Bending Moment

OMS vessel with single liner depression of 40 mils depth showing destabilizing effect of 15% stiffness loss due to Bauschinger Yield Effect during liner compression at end of proof cycle.

Final bending moment distribution at $p_{vessel} = 0$ WITHOUT Bauschinger yield effect.

- $p_0 = 956$ psi
- $p_{ref} = 2,650$ psi
- $N_{I,u} = -9,172$ lb/in.
- $N_{I,p} = -13,570$ lb/in.
- $K_p = 0.45$
- $K_{p,f,max} = 0.30$
- $x_{hat} = 0.65$ in.

Final bending moment distribution at $p_{vessel} = 0$ WITH Bauschinger yield effect causing liner stiffness softening after 72 lb-in./in.

- $E_t = 16,500,000$ psi
- $E_{LB} = 14,000,000$ psi
- $V_t = 0.342$
- $t_i = 0.106$ in.
- $E_{O,t} = 250,000$ psi
- $E_{O,t,0} = 25,000$ psi
- $t_0 = 0.739$ in.
- $R_i = 19.19$ in.
Effect Changing Depression Depth on Interface Pressure

OMS Vessel with Single Liner Depression of Various Depths

- Interface pressure distributions at zero vessel pressure.
- Interface pressure distributions at proof pressure.

**Parameters:**
- $E_I = 16,500,000$ psi
- $v = 0.342$
- $t = 0.106$ in.
- $E_{O1} = 250,000$ psi
- $E_{O1,0} = 25,000$ psi
- $t_0 = 0.739$ in.
- $R = 19.19$ in.
- $p_0 = 956$ psi
- $p_{ref} = 2,650$ psi
- $N_{I,u} = -9,172$ lb/in.
- $N_{LP} = -13,570$ lb/in.
- $K_p = 0.45$
- $K_{p,max} = 0.30$
- $X_{hat} = 0.65$ in.
Effect Changing Depression Depth on Bending Moment

OMS Vessel with Single Liner Depression of Various Depths

bending moment distributions at proof pressure

final bending moment distributions at zero vessel pressure.

$M_{\text{max, elastic}} = 240 \text{ lb-in./in}$

$K_f M_{\text{max, elastic}} = 108 \text{ lb-in./in}$

$K_p M_{\text{max, elastic}} = 72 \text{ lb-in./in}$

$K_{pf, max}$ Baushinger yielding effect likely active

- $E_I = 16,500,000 \text{ psi}$
- $\nu_I = 0.342$
- $t_I = 0.106 \text{ in.}$
- $E_{O,t} = 250,000 \text{ psi}$
- $E_{O,t,0} = 25,000 \text{ psi}$
- $t_o = 0.739 \text{ in.}$
- $R_I = 19.19 \text{ in.}$
- $p_0 = 956 \text{ psi}$
- $p_{\text{ref}} = 2.650 \text{ psi}$
- $N_{l,u} = -9.172 \text{ lb/in.}$
- $N_{l,p} = -13.570 \text{ lb/in.}$
- $K_p = 0.45$
- $K_{pf, max} = 0.30$
- $x_{\text{hat}} = 0.65 \text{ in.}$
Conclusions

- The key result is that depression depths of up to 40 mils can be tolerated but above 40 mils, the Bauschinger effect dominates and buckling become increasingly likely.

- Note that in the absence of a liner depression, the liner is elastically stable in hoop compression even at overwrap-liner interface pressures approaching 6000 psi.

- So far a 40 mil depression has been seen but only in the thickened weld band, where this analysis does not apply.
Accelerated Stress Rupture Test (ASRT)
ASRT Overview

- Obtain a stress rupture data point from an Orbiter COPV for comparison to the baselined COPV stress rupture reliability model.
- Single data point could not validate current model but could provide increased confidence in the model predictions.
- It was necessary to Accelerate time through holding the tank at increased temperature or pressure.
  - COPV test team decided to maintain pressure at 4850 psia and increase temperature to 130 deg F (Phase 1) & 160 deg F (Phase 2).
- This test was designed to encompass multiple accelerated stress rupture pressurized test phases:
  - Phase 1: “moderately accelerated test” 35,575 total effective hours
    - Designed to achieve the midpoint of model predicted Point reliability.
  - Phase 2: “aggressively accelerated test” 86,745 total effective hours
    - Designed to determine if the test article will exceed the 95% confidence interval of the stress rupture model Point reliability prediction.
  - Phase 3 & continued for engineering value 113,000 total effective hours
    - Test proceeded to failure, to obtain the first measurement of a stress rupture failure.
    - Pressure, Temperature: 5200 psia, at 160°F (Phase 3)
    - Pressure, Temperature: 5400 psia, at 173°F (Phase 4)
Accelerated Stress Rupture Test

Test article eventually failed after 3,100,000 effective hours
Bayes Analysis and Reliability Implications of Stress-Rupture Testing of a Kevlar/Epoxy COPV using Temperature and Pressure Acceleration, AIAA 2009-2569

With Pappu L.N. Murthy, NASA Glenn Research Center
ASRT Success Criteria (to increase model confidence):

Approach 1: Will the tank survive as long as the model predicts?
   Compare SN007 life to model point reliability.
   Problem – Uncertainty in model not considered.

Approach 2: How can one statistically accept current model based on a single data point?
   Hypothesis: Assume Model overpredicts lifetime.
   Question: Does SN007 lifetime allow us to reject hypothesis by lasting longer than criterion?
   If so, then data point confirms model.

Approach 3: Can a statistical argument be made to better select among two (or mode) candidate Orbiter Stress Ratio models?
   Method: Establish lifetime predictions for candidate models and compare
Uncertainty as a function of reliability for the different Stress Ratio Models.
Main Finding and Where We Seem to be Today

**SN006/7 key parameters:**
- SR M2 = 0.599 at MOP \( \alpha_2 = 59 \)
- SR M4 = 0.653 at MOP \( \alpha_4 = 39 \)
- \( \beta_{orb} = 1.625 \) (cv = 0.08)
- \( \beta_{orb} = 2.45 \) (cv = 0.30)

**Worst stress ratio, best shape parameter scenario:**
- \( p_{\beta_{orb}} = 1 \), \( p_{M2} = 0 \)
- \( R_{pt} = 0.99981 \)
- \( R_{mean} = 0.99926 \)
- \( R_{95} = 0.9968 \)

**Worst case scenario:**
- \( p_{\beta_{orb}} = p_{M2} = 0 \)
- \( R_{pt} = 0.99907 \)
- \( R_{mean} = 0.9984 \)
- \( R_{95} = 0.9950 \)

**Best case scenario:**
- \( p_{\beta_{orb}} = p_{M2} = 1 \)
- \( R_{pt} = 0.9999988 \)
- \( R_{mean} = 0.999985 \)
- \( R_{95} = 0.999926 \)

**50-50 prior:**
- \( p_{\beta_{orb}} = p_{M2} = 1/2 \)
- \( R_{pt} = 0.999937 \)
- \( R_{mean} = 0.99938 \)
- \( R_{95} = 0.9969 \)

**SLP 11/20/07**
ASTR Summary: Update to Orbiter Reliability Model

- The ‘success’ of the Accelerated Stress Rupture Test has not been fully investigated.

- Orbiter Project made a conscious decision not to update the reliability model based on a successful Accelerated Stress Rupture Test
  - Increasing the model fidelity was not needed to make flight decisions
  - Rationale was to spend resources to make the vehicle fly safer and not to update models and charts

- COPV Analysts believe that should the model be updated, the Bayesian analysis is justification for adopting the competing stress ratio model.
  - Bayesian Approach has been peer reviewed in the literature but has not fully been vetted by the Space Shuttle Program and NASA
  - Alternate stress ratio model would decrease the flight risk by one order of magnitude (or add one ‘9’ to the reliability predictions).
Raman NDE Technique

Use of Raman Spectroscopy and Delta Volume Growth from Void Collapse to Assess Overwrap Stress Gradients Compromising the Reliability of Large Kevlar/Epoxy COPVs, AIAA 2009-2566

With Jeffrey Eldridge, Glenn Research Center.
Potential technique to assess COPV health through Non Destructive Evaluation (NDE) Techniques.

Instead of estimating the stress from the change in tank volume, hypothesis is to measure the strain using a Raman Spectrometer on the exterior of the tank and correlate to stress through the thickness of the overwrap. (Nobel Prize 1930)
Kaiser Measurements: SN001

Measurements have precision to distinguish different wraps.

Note: band numbers in Raman plots are wrap numbers -1

thickened liner approaching boss with transition to membrane thickness at wrap 6

bands 6-14
average = 0.1002%
bands 22-30
average = 0.0943%

bands 6-14
average = 0.2619%
bands 22-30
average = 0.2545%

1000 psi
0 psi
Stress Through Overwrap Thickness

Residual Elastic Hoop Strain Profiles Through the Overwrap Thickness of OMS Vessels with Increasing Void Content and Delta Volumes

Phoenix Stress Ratio Model combining:
(1) recoverable elastic strain at low delta volumes, and
(2) increasingly nonlinear void compaction at high delta volumes

original proof dVs in³
350
325
300
275
260
225
200
175

Residual elastic fiber strain, microstrain

Relative position through the overwrap thickness, z/tc

Raman strains

linerr interface

outer surface
Raman as an NDE Technique

SLP spherical shell analysis: predicted surface strain vs delta volume from proof (boss effects and creep ignored)

Renishaw Series 100 spectrometer, RP20V probe

Kaiser Raman system with PHAT probe (current system)

S/N 20, 18 and 21 pre-Raman values and possible range

Three remaining vessels in service with largest dV estimates
SN020 – currently carried as 310 in³. Would Raman measurements change current risk level? update reliability to two 9’s or four 9’s?
Conclusion

- Variability and Uncertainty in Orbiter Fleet has motivated the Orbiter Engineering Team to investigate alternative approaches to assess safety on flight COPV.
- NDE Technique of Raman Spectroscopy is shown to quantitatively assess tank health and preliminary results show the method could provide a screen to detect unreliable flight articles.
Future of COPV

- Composite vessels used extensively in space applications
## International Space Station: Current Configuration

<table>
<thead>
<tr>
<th>COPV</th>
<th>Geometry</th>
<th>Media</th>
<th>Volume</th>
<th>On-Orbit Fill Pressure</th>
<th>Maximum Design Operating Pressure</th>
<th>Minimum Design Burst Pressure</th>
<th>Fill/Burst Pressure Ratio</th>
<th>Approx Design Safety Factor</th>
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<td>HPGT</td>
<td>37.89 Ø</td>
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Ø = Diameter; HPGT = High Pressure Gas Tank; NTA = Nitrogen Tank Assembly; PCU = Plasma Contactor Unit; SAFER = Simplified Aid for Extravehicular Activity Rescue; VGA = Verification Gas Assembly; GBA = Gas Bottle Assembly; AMS = Alpha Magnetic Spectrometer; VCAM = Vehicle Cabin Air Monitor; GBU = Gas Bottle Unit
Nitrogen Oxygen Recharge System:

Shuttle currently supplies gasses to ISS

Post Shuttle Retirement COPVs will deliver O2 and N2.
Backup Charts