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.

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Acknowledgements (COPV Team Members)

NASA (JSC):
- **Howard Flynn**
- **Scott Forth**
- **Rick Russell**

Boeing:
- **Valery Aksamentov**
- **John Chan**
- **Don Varanauski**

USA:
- **Horace Lamberth**
- **Jesus Macias**
- **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
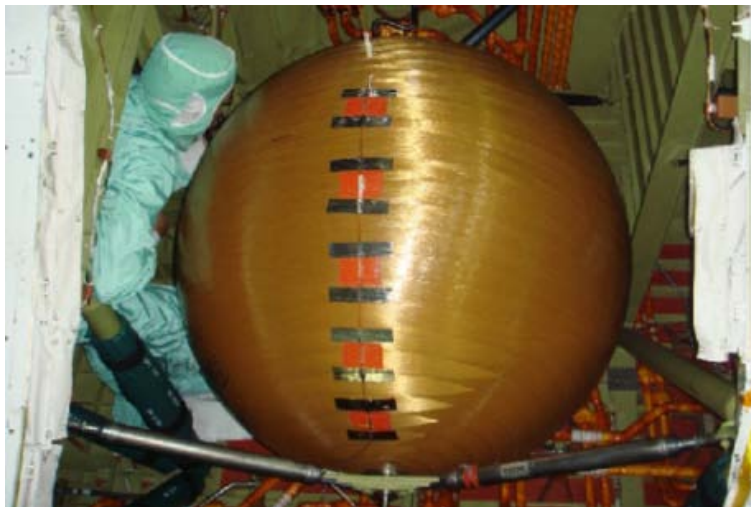 Seven 26" He
Orbital Maneuvering System (OMS)
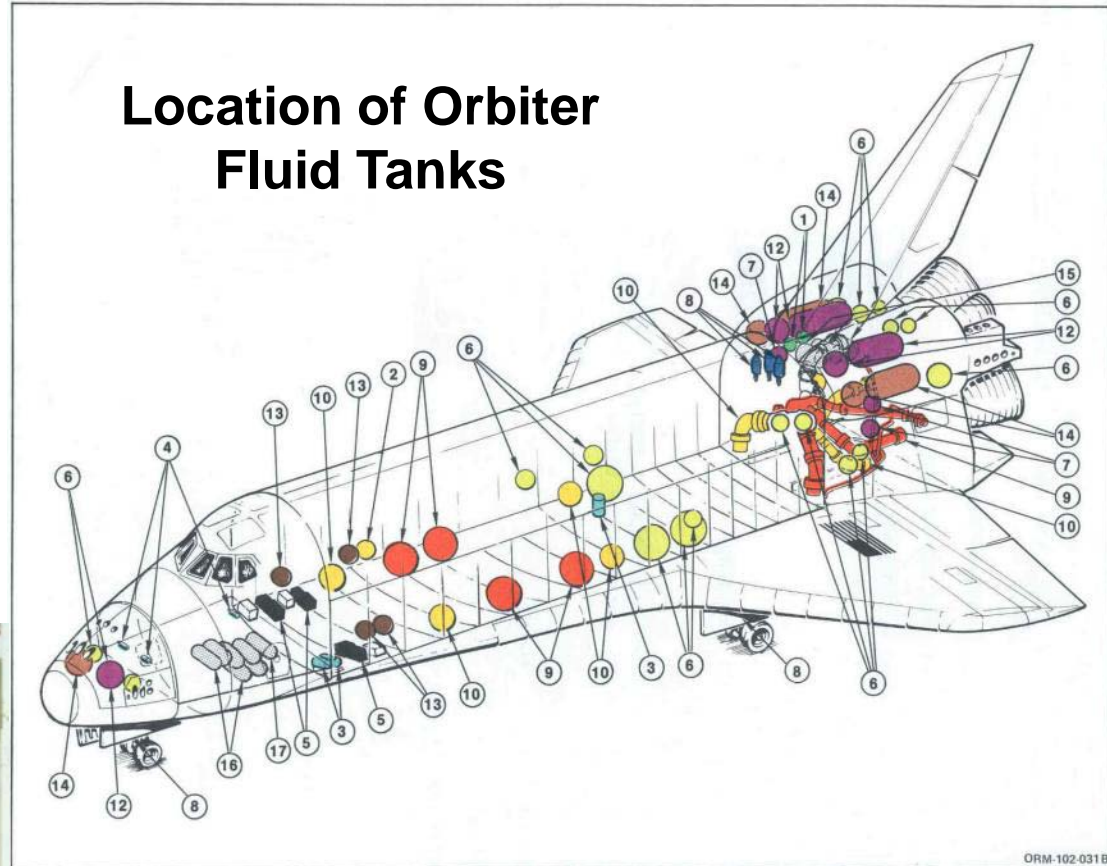 Two 40" He
Reaction Control System (RCS)
  Two 19" He (each)
  Left, Right and Forward
Environmental Control and Life Support
  System (ECLSS)
  Four to Six 26" N_2

Location of Orbiter Fluid Tanks

ORM-102-031B

- 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)

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COPV Weight Savings

- 24 Kevlar COPVs saved approximately 752 pounds per Orbiter Vehicle (compared to an all metal tank design)
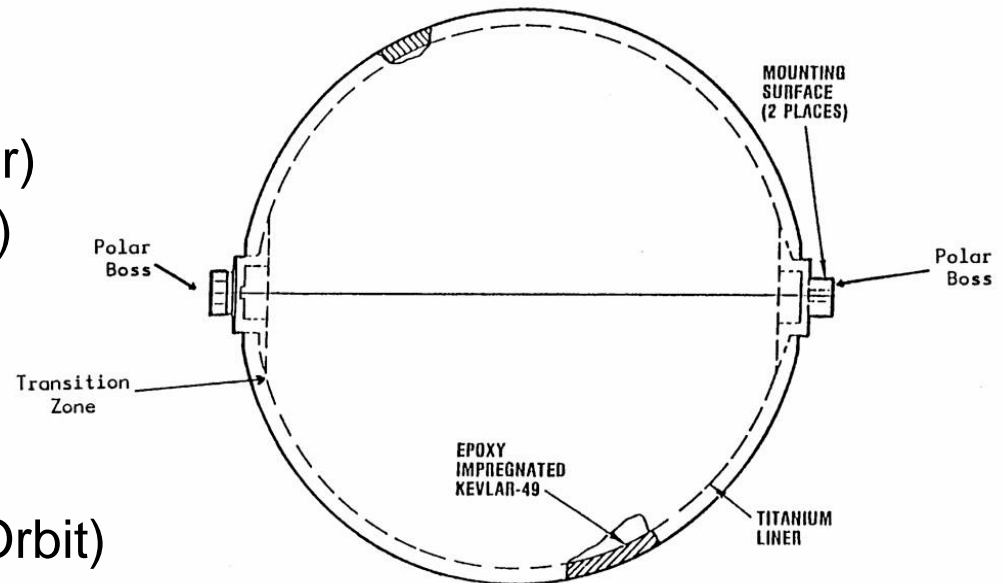
- Orbiter Dry Weight
  - 176,056 pounds (Endeavour)
  - 176,419 pounds (Discovery)
  - 176,413 pounds (Atlantis)

- 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

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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: hen 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 envelope 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

	LLNL Vessels	Fleet Leaders	Fleet Vessels
Diameter (in)	4.5	10.4	19 - 40
Liner Material	1100 Al	5086 Al	Ti-6Al-4V
Liner Thickness (in)	0.04	0.04	0.044 (RCS He)- 0.104 (OMS He)
Overwrap Thickness (in)	0.04	0.25	0.285 (RCS He)- 0.739 (OMS He)
Overwrap Pattern	delta axi-symmetric	Complex	Complex
Resin	DER 332/Jeffamine T-403	LRF-092	LRF-092
Fiber	Kevlar 49 - 380 Denier	Kevlar 49 - Type 969	Kevlar 49 - Type 969
Quality Control	Little, if any	High	High
# Build Spools	One	Multiple	Multiple
Pre-test Load	None	Proof test	Proof test

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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)

BDS | Space Exploration | Engineering & Mission Assurance

COPV Risk →

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

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

SPACE SHUTTLE
OMS/RCS AFT PROPULSION SUBSYSTEM
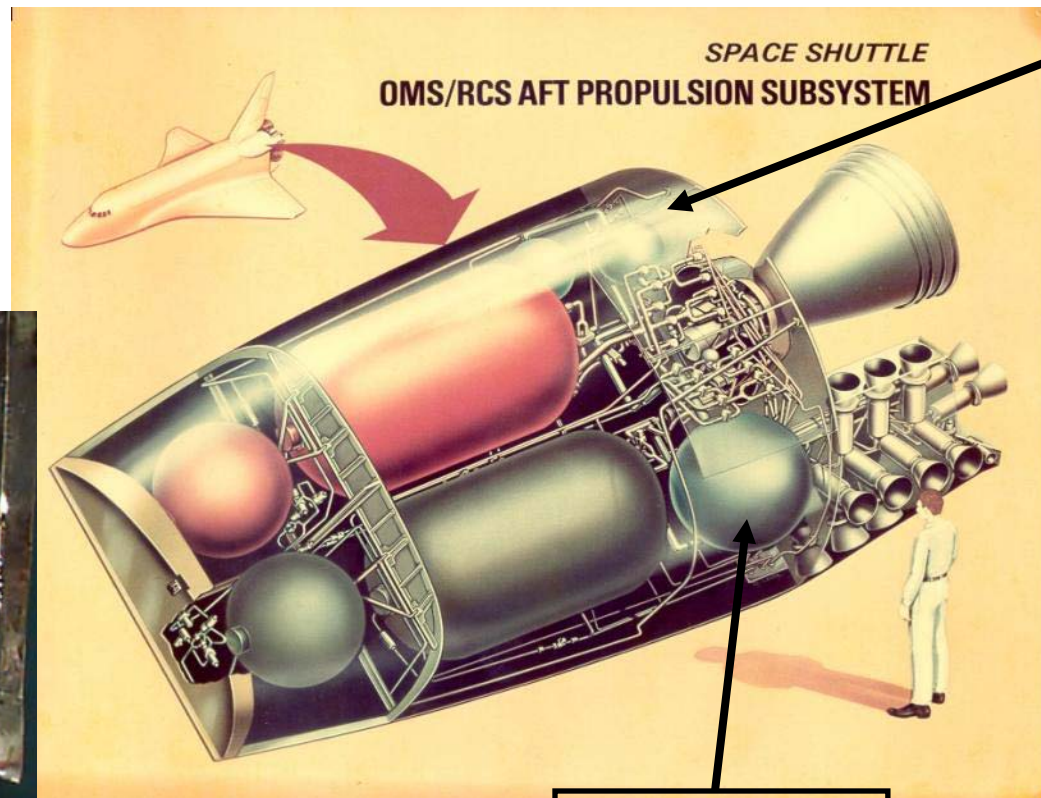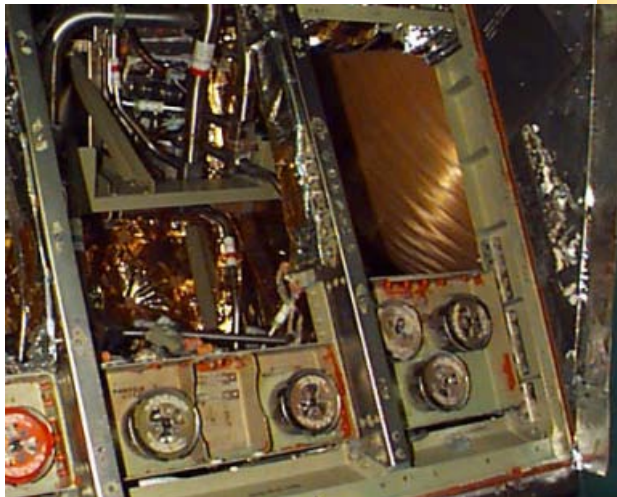
18" RCS He Tanks

40" OMS He Tank

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Margin Improvement Options (OMS/RCS COPV Replacement)

Option	Description	Margin Post Implementation	Relative Complexity	Risks	Schedule: Hardware On Dock	Relative Cost
1A	Replace Existing Tanks with new drop-in MC282-0082-XXXX replacements	Acceptable	**Low:** • New Tank • OMS 40" Tank Replacement	**Medium:** • Tank procurement schedule • OMS Pod skin damage	18 months	Medium
1B	Replace Existing Tanks with nearest COTS equivalent	Acceptable	**High:** • Requires extensive redesign of OMS Pod structure and/or helium system	**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	24 - 36 months	High
2	Swap OMS 40" tanks with MPS 40" tanks	**UNACCEPTABLE** Minimal improvement	**Low:** • 40" OMS Tank Replacement • 40" MPS Tank Replacement	**Medium:** • OMS Pod skin damage • Aft compartment damage	0 months	Low
3	Add an additional tank or tanks to increase OMS system volume to reduce pressure	**Acceptable for OMS; Not Applicable to RCS**	**High:** • New plumbing/tank mounting provisions in aft • New instrumentation (temp sensors) • New interface (Aft/OMS) • Recert of OMS system etc. • 26" tank procurement	**High:** • System design • Tank procurement schedule • Addition of new failure modes • Damage in Aft Compartment during mod • RCS tank margins	14 - 18 months (assumes use of 2 tanks from Logistics inventory)	Medium
4	Strengthen existing tanks by adding additional layers of overwrap	Unknown	**High** • Requires extensive development, analysis, and qualification effort	**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	14 - 18 months	Medium-High

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OMS Tank Removal Replacement Feasibility

Option	Description	Feasibility	Relative Complexity	Risks
1	Remove RCS stinger and extract tank out end of Pod	Feasible	**High:** • Requires cutting 10 RCS prop. lines • Thrusters must be refurbished	**Medium:** • RCS system damage • Stinger structural reattacment
2	Remove OMS NTO tank and extract He tank out opening	**Not Feasible** Bulkhead opening is too small	**High:** • Would require extensive redesign & modification of OMS Pod Structure	**High:** • OMS Pod modification would be extensive
3	Remove Pod aft outboard skin and extract tank out opening	Feasible	**Medium:** • Requires removal of 180 HiLoks • Requires removal of NTO tank	**Medium:** • OMS Pod skin damage

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

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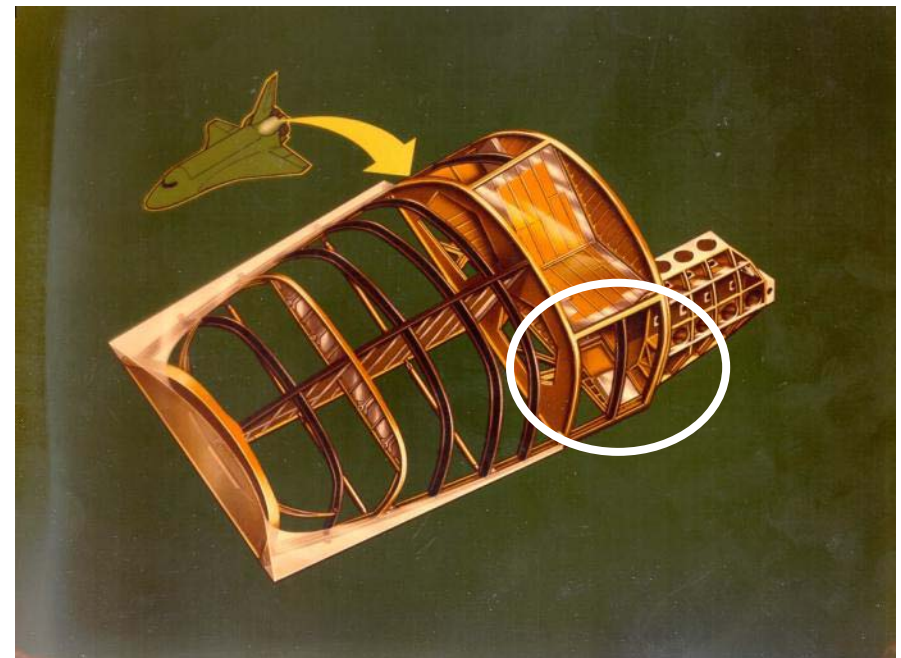
MPS Tank Replacement of Existing Flight Spares

- **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**

Operational Improvements

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

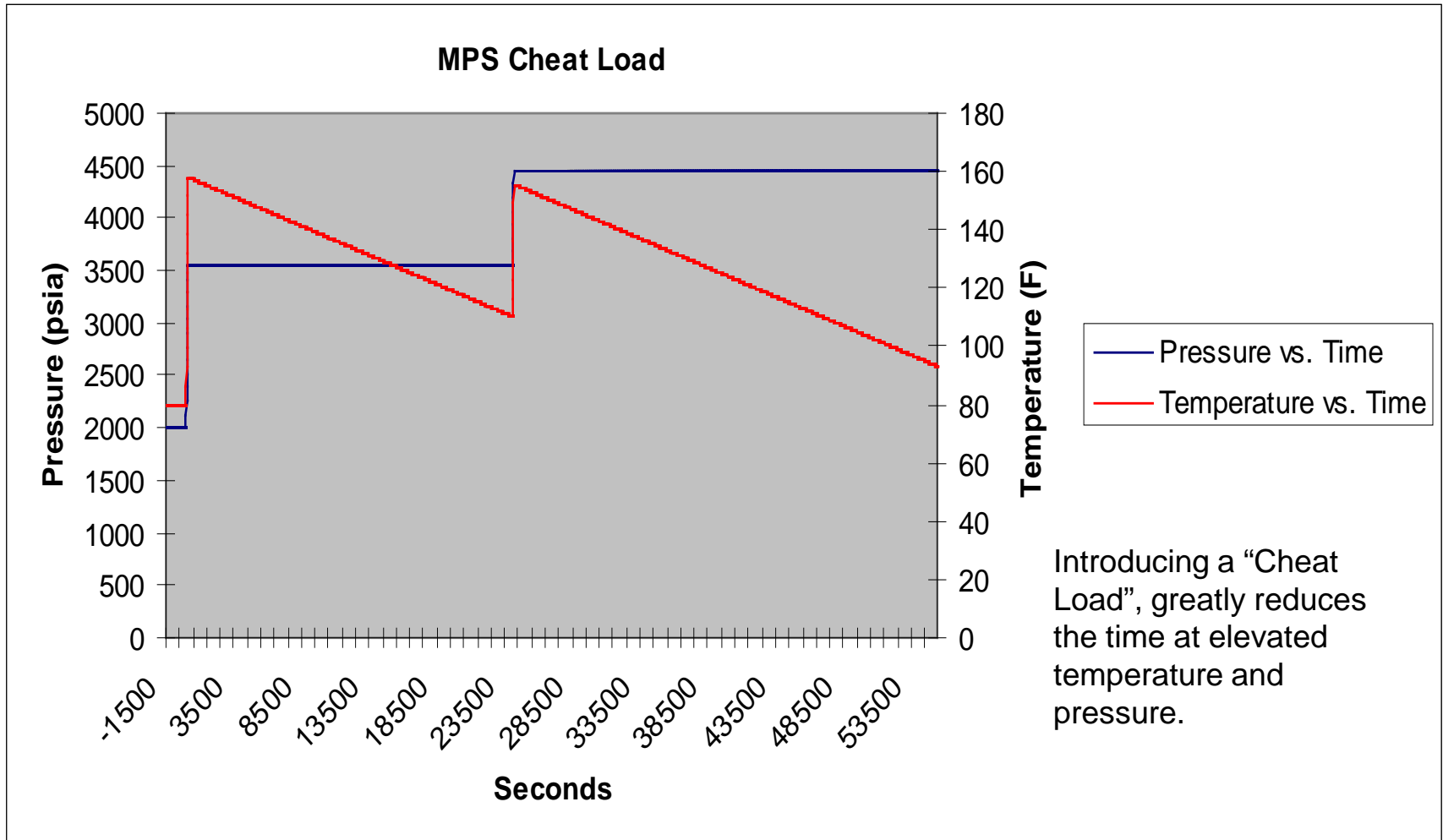[#]Temperatures in the past had gone to 180ºF (82ºC) or higher

15

Typical MPS Load Profile

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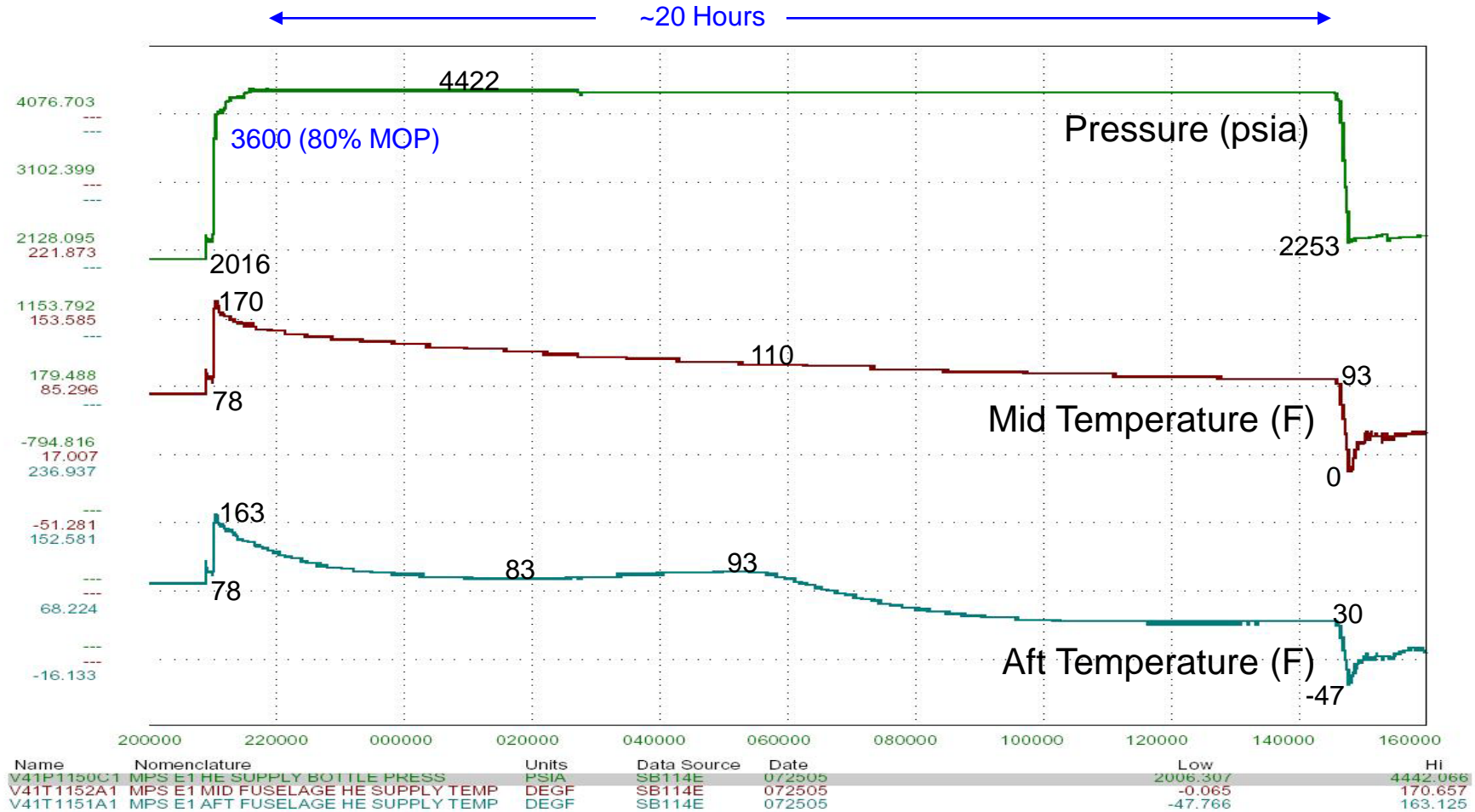
Two-Stage Loading Process

MPS Cheat Load

Introducing a "Cheat Load", greatly reduces the time at elevated temperature and pressure.

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Operational Improvements Summary

Subsystem	#	Old Load	New Load	Cheat Load	Temp Limits (deg F)	Original Effective Hours	Effective Hours (2 day)
OMS (Full Load)	2	T-12	T-6	Y	100	200	105
RCS: AFT (L/R)	4				120	272	135
RCS: F	2					98	31
MPS 40"	3			Y		240	90
MPS: AFT	3			Y		225	93
MPS: MID	4			Y		187	65
ECLSS	4-6	T-90	T-70	N	110	2,500	1,468

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

Flight	Vehicle	Date	OMS (L & R)		MPS (L, R & C)		
STS-123	OV-105	3/11/08	29.6	12.6	41.8	36.9	45.4
STS-124	OV-103	5/31/08	14.5	16	39.6	42.2	36.5
STS-126	OV-105	11/14/08	33	15	32.9	30.4	38.1
STS-119	OV-103	3/15/09	23.4	23.9	51.3	57.1	47
STS-125*	OV-104	5/11/09	100	106	66	63	70.9
STS-127	OV-105	7/15/09	63.2	24	66.9	57.7	74.8
STS-128	OV-103	8/28/09	26.7	29.2	101.7	109.1	94.4
STS-129	OV-104	11/16/09	14.2	15.6	42.6	42.7	47.7
Projected Hours Standard OMS * Full OMS Load			35 hrs/flight * 105 hrs/flight		90 hrs/flight		

- •STS-125 carried a Full OMS Load.
- •Red indicates accumulated hours exceeding projections.

Orbiter Reliability Model Key Features:

Kevlar database to consider lifetime as a function of stress ratio in fiber (effective fiber stress level divided by fiber strength) at burst

- **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,

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

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

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

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

Weibull shape parameter for strength

$$\left(\rho_1 + 1\right)\beta_1 = \left(\rho_2 + 2\right)\beta_2 = \alpha$$

Kevlar Industry Database

■ **Problem 1: Fiber volume fraction influences effective mean *fiber strength* of Kevlar/epoxy strands (after rule of mixtures calculation)**
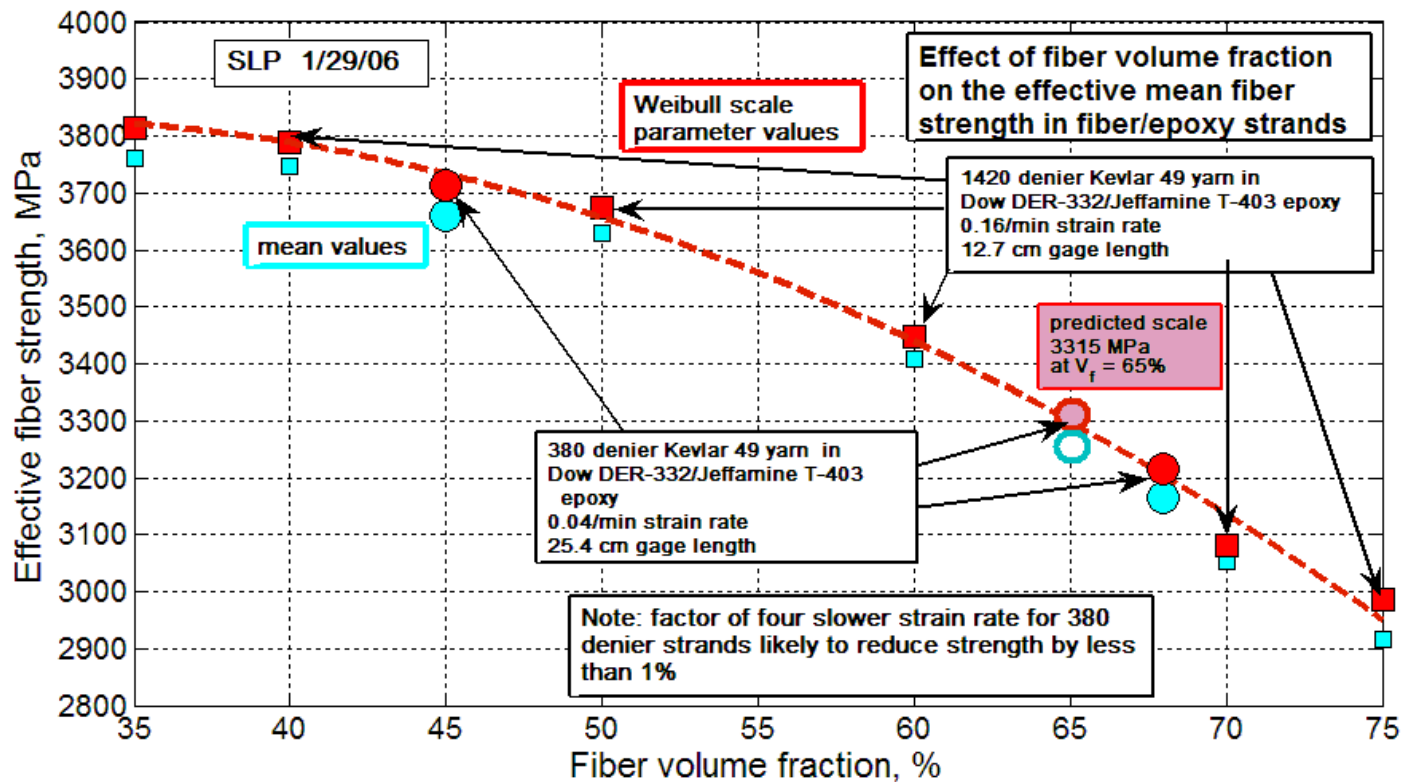
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Kevlar Industry Database

- **Lifetime vs fiber stress for various Kevlar 49/epoxy strands (volume fraction effect originally confounded stress ratio concept)**
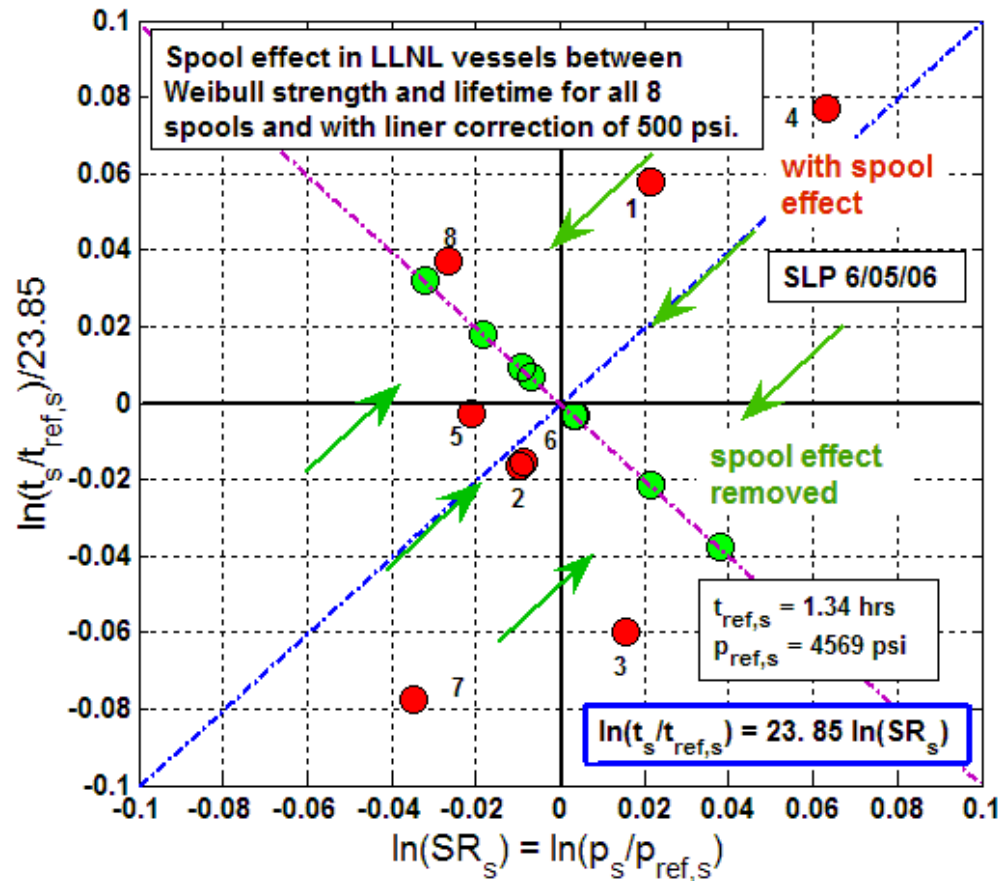
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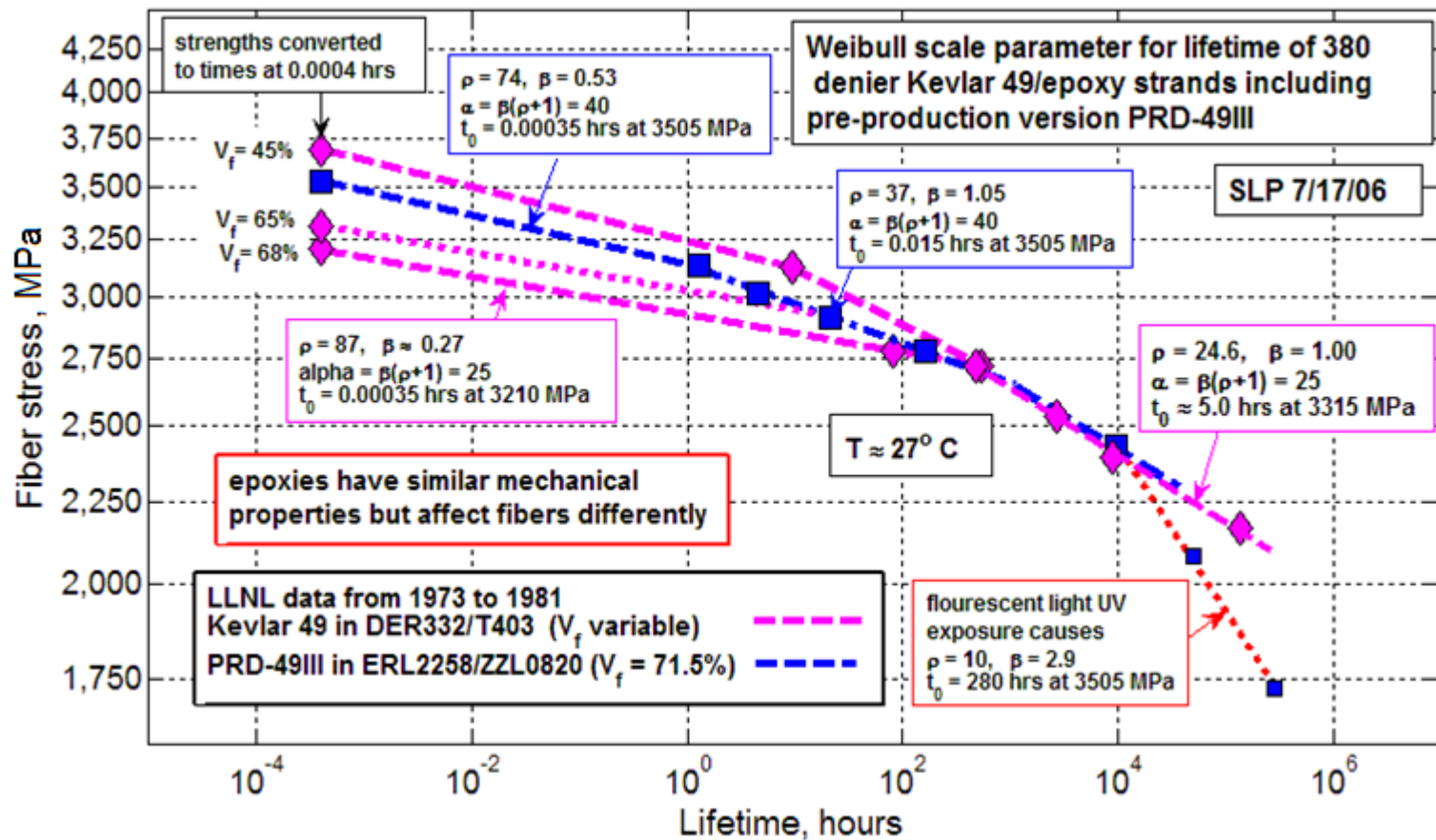
Kevlar Industry Database

- **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**
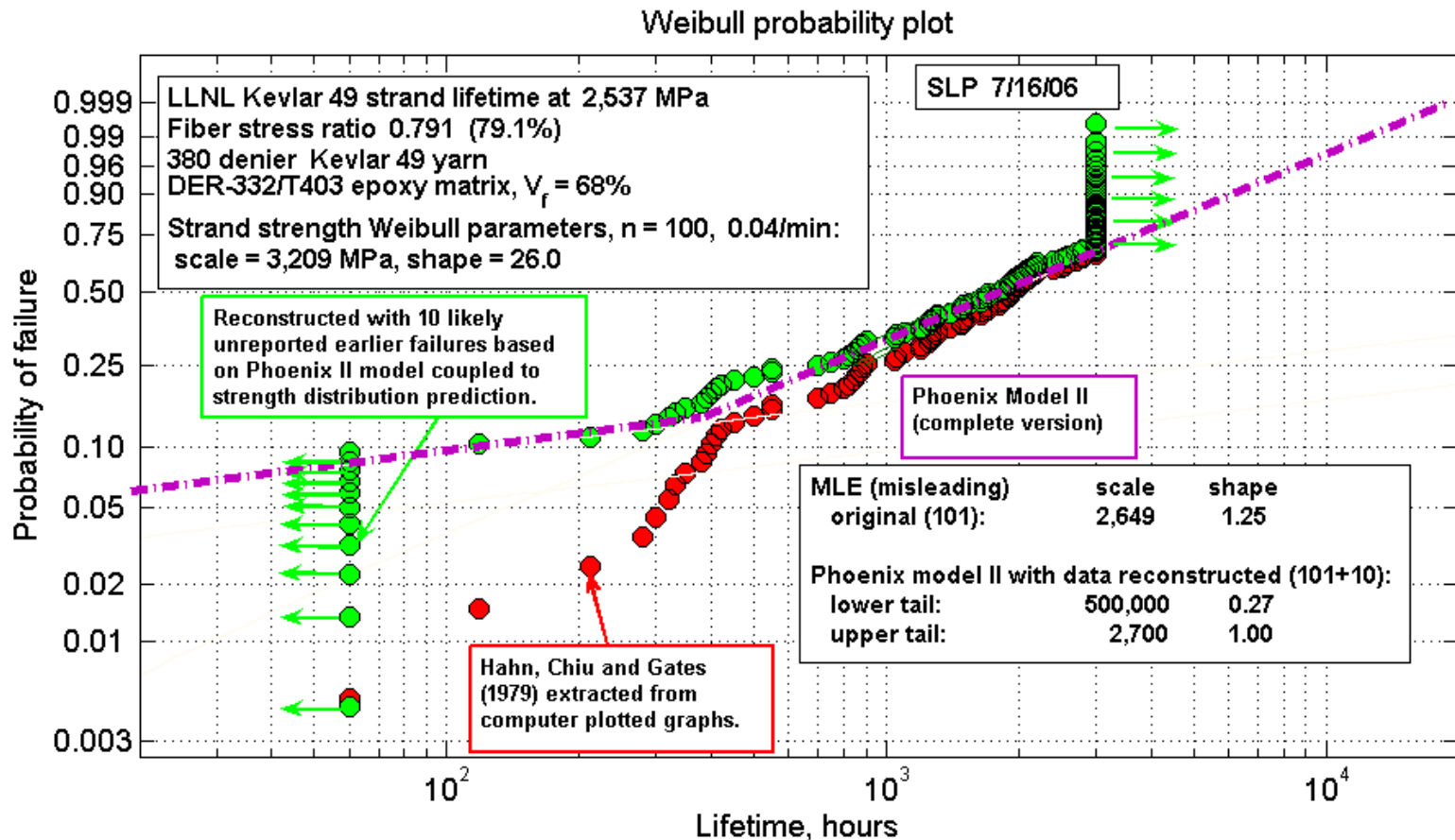
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- **Problem 3: Since 30 vessels were made from each spool (7 spools) serious spool effects emerged, so had to develop analytical technique to remove spool-to-spool effects uniformly between strength and life**

Spool effect in LLNL vessels between Weibull strength and lifetime for all 8 spools and with liner correction of 500 psi.

SLP 6/05/06

with spool effect

spool effect removed

$t_{ref,s} = 1.34$ hrs
$p_{ref,s} = 4569$ psi

$$\ln(t_s/t_{ref,s}) = 23.85 \ln(SR_s)$$

y-axis: $\ln(t_s/t_{ref,s})/23.85$

x-axis: $\ln(SR_s) = \ln(p_s/p_{ref,s})$

- **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

Weibull probability plot

LLNN and duPont -DOE Kevlar 49 spherical vessel burst pressure data corrected for liner support and spool effects

duPont-DOE vessel Weibull parameters with censoring of leakers and other anomalies, and adjusted for 286 psi of liner support:
shape [95% CI]: 37.1 [23.2, 59.4]
scale (psi) [95% CI]: 4535 [4457, 4615]

duPont-DOE

LLNL including outlier vessel #82 (spool 3)

After liner correction duPont-DOE vessels now only 1.0% weaker than LLNL vessels

LLNL original data

LLNL with #82 outlier removed

SLP 7/16/06

LLNL vessel Weibull parameters:
Adjusted for spool effect (spool 7 included), liner support of 500 psi and outlier removed:
shape [95% CI]: 40.1 [306, 52.6]
scale (psi) [95% CI]: 4581 [4540, 4622]
Original:
shape [95% CI]: 25.2 [19.7, 32.2]
scale (psi) [95% CI]: 4604 [4540, 4670]

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Kevlar Industry Database

- **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.*
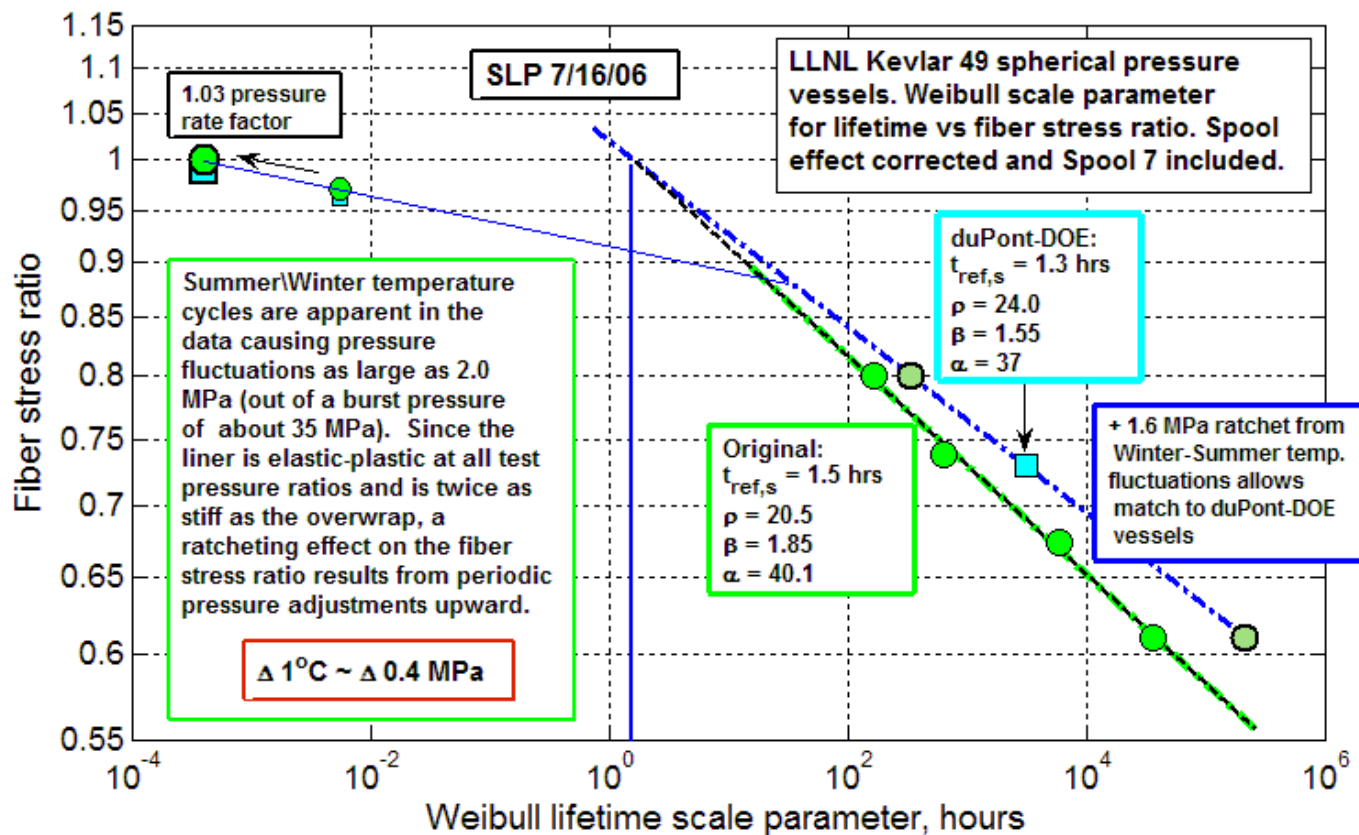
Kevlar Industry Database

- **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)**
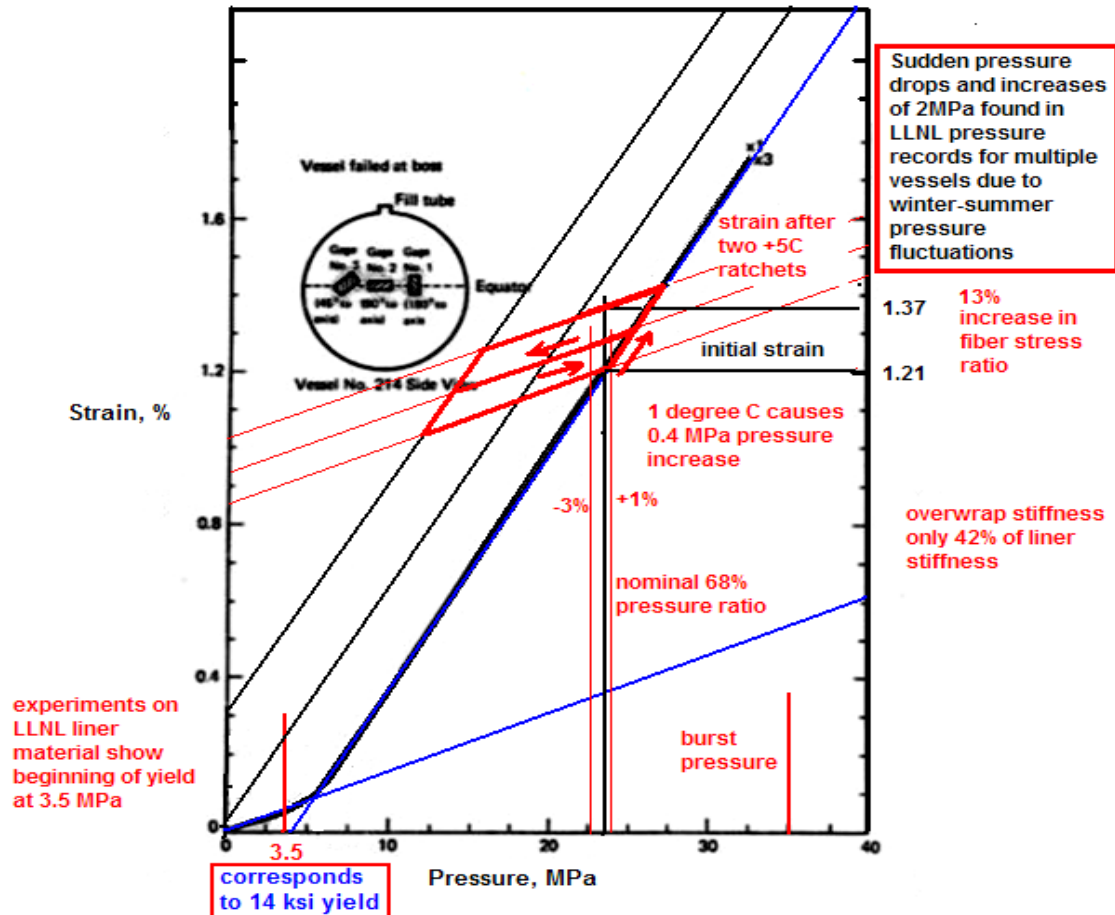
30

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*
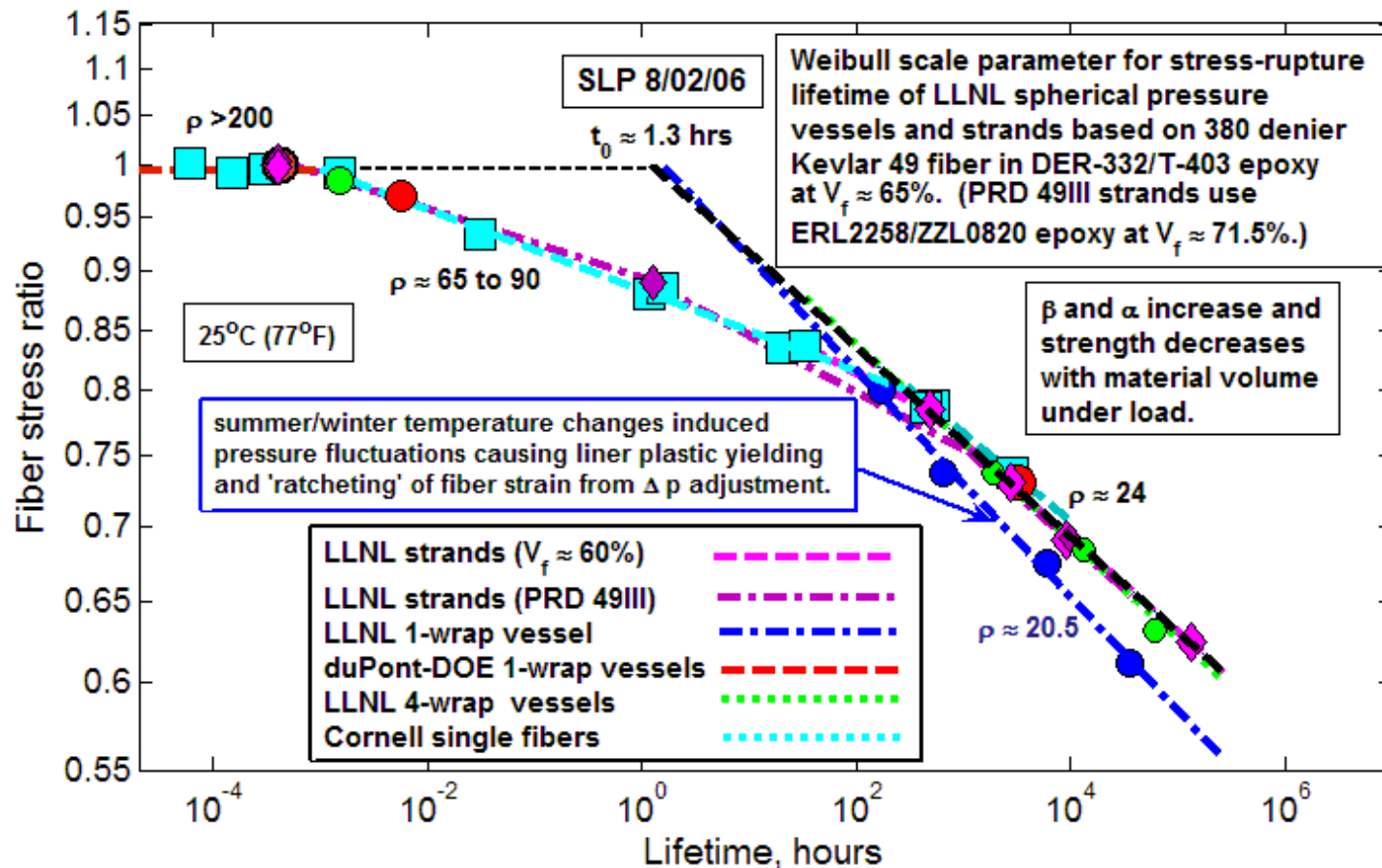
31

Kevlar Industry Database

- **Data on temperature effects finally resolved the issue $\rho \propto 1/T$ was key discriminator**

Dependence of Weibull scale parameter for lifetime on fiber stress ratio and absolute temperature in °K

SLP 8/15/06

$SR_0 = 2.86$

$t_0 = 1.64 \times 10^{-11}$ hrs

LLNL vessels believed to have suffered a ratchet effect on strain over time due to summer-winter temperature fluctions that plastically yielded the soft Al liner (equal in thickness to the overwrap). This was made worse by pressure corrections. Consequently the LLNL vessel model parameters slightly underestimate elevated temperature performance of duPont-DOE and NASA fleet leader vessels.

$\rho = 24$, $\beta = 1.67$
$t_{ref} = 1.43$ hours
$\alpha = \beta\rho = 40$

■ Single Kevlar 49 fibers

◆ Kevlar 49/epoxy strands

◉ Kevlar 49/epoxy spherical pressure vessels

$\rho \, \alpha \, 1/T$

80°F
150°F
175°F
200°F
230°F

Stress Ratio (y-axis) vs Lifetime, hours (x-axis)

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Stress Ratio of Orbiter COPV

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

- **Consider 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**
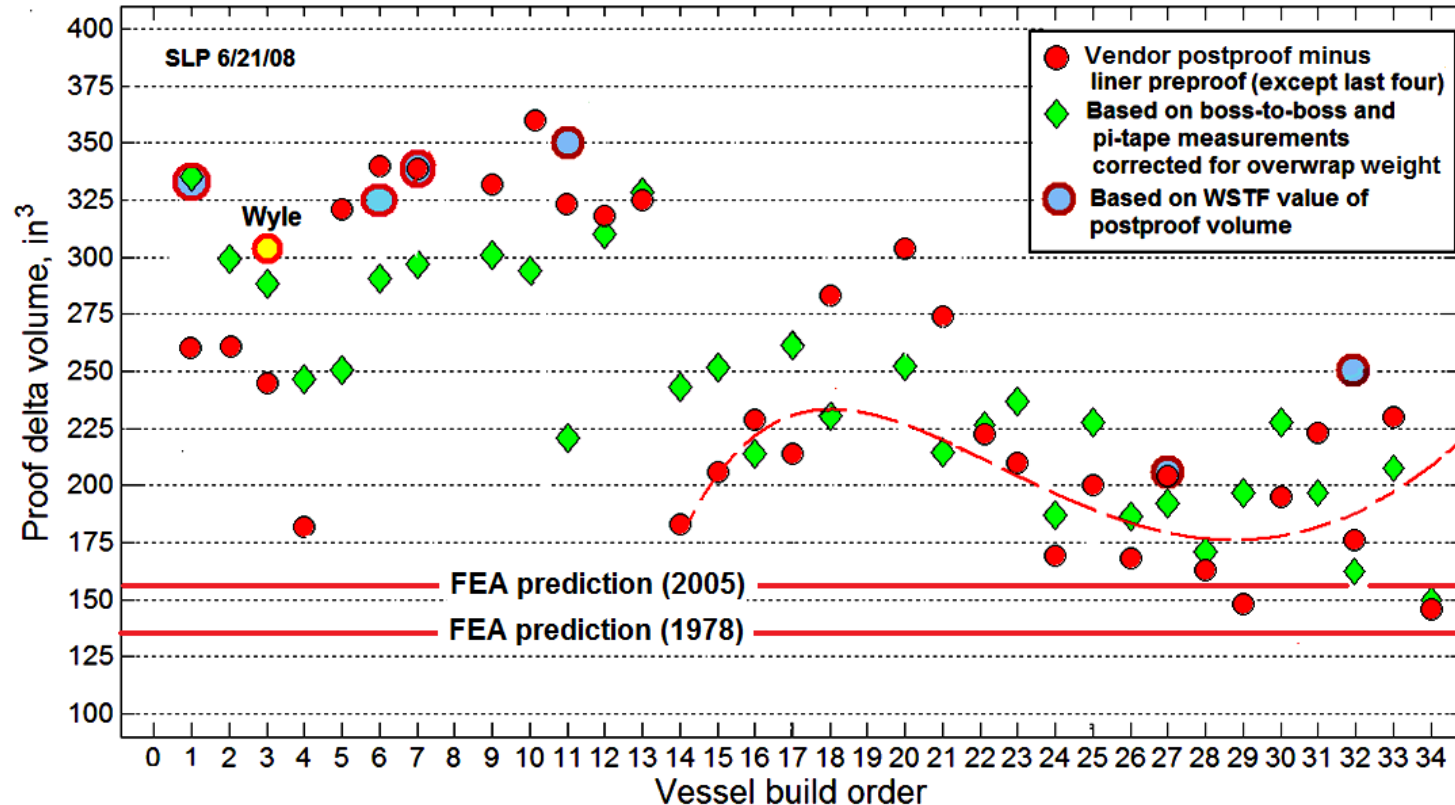
Vessel Fiber Stress Ratio tied to performance of individual 40" Tanks based on original acceptance test data.

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:**

$$\text{(power-law, } \rho \text{, Weibull, } \beta \text{, } t_{\text{ref}} \text{, etc.)}$$

- **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.**

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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.**

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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:**

$$S\left(p,T_{\mathrm{el}}\right)=\Phi^{\left(T_{\mathrm{el},K}-T_{\mathrm{ref},K}\right)/T_{\mathrm{el},K}}\,S\left(p,T_{\mathrm{ref}}\right)^{T_{\mathrm{ref},K}/T_{\mathrm{el},K}}\,,$$

$$\Phi=2.86,\quad T_{\mathrm{ref,K}}=300^{\circ}\mathrm{K}\quad\left(80.6^{\circ}\mathrm{F}\right),\quad \rho\equiv\rho_{\mathrm{ref}}=24$$

$$\rho_{\mathrm{el}}=\rho\,T_{\mathrm{ref,K}}\big/T_{\mathrm{el,K}}$$

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

$$\tilde{t}\left(p_{\mathrm{el}},T_{\mathrm{el}}\right)=\tilde{t}\left(p_{\mathrm{ref}},T_{\mathrm{ref}}\right)\left[\frac{S\left(p_{\mathrm{ref}},T_{\mathrm{ref}}\right)}{\Phi}\right]^{\rho\left(1-T_{\mathrm{ref}}/T_{\mathrm{el}}\right)}\left[\frac{S\left(p_{\mathrm{ref}},T_{\mathrm{ref}}\right)}{S\left(p_{\mathrm{el}},T_{\mathrm{ref}}\right)}\right]^{\rho\left(T_{\mathrm{ref}}/T_{\mathrm{el}}\right)^{2}}$$

Orbiter Reliability Model developed in MatIab

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Life of Program Reliability Estimate

Two Day Launch Scrub - PRCB 10/18/2007

From STS-118
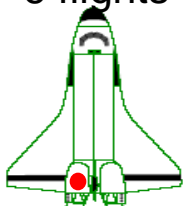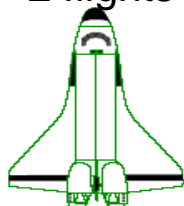
OV-103	OV-104	OV-105
6 flights	2 flights	7 flights
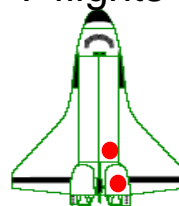
Life of Program COPV Reliability 15 Flights Combined

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

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

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 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.

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OV103 COPV Risk Apportionment 2007-Nov (with hours, post STS-120)

Aggregate Subsystem Risk Per Hour

Event	Timeline	L-Days	Risk Per Hour	Risk	1 in ... Risk	OMS	MPS	RCS	ECLSS
Prior to Loading	-	72.00	0		0				
ECLSS(L) Pressurization	From	72.00	1.58E-09						
	To	71.75	1.58E-09	9.48E-09	105524752				1.58E-09
ECLSS Hold	From	71.75	2.12E-10						
	To	4.54	2.12E-10	3.41E-07	2930297				2.1157E-10
Stage 1 Load (Cheat) (Pad Clear 1)	From	4.54	5.66E-07						
	To	4.00	5.66E-07	7.42E-06	134781	5.6558E-07	2.7890E-10	2.9494E-10	2.1157E-10
Stage 1 Hold	From	4.00	1.21E-07						
	To	3.36	1.21E-07	1.85E-06	540559	1.1998E-07	2.1880E-10	4.9958E-10	2.1157E-10
Stage 2 Load (Pad Clear 2)	From	3.36	4.38E-06						
	To	2.96	4.38E-06	4.20E-05	23784	4.3265E-06	2.7187E-08	2.5714E-08	2.1157E-10
Stage 2 Hold	From	2.96	9.10E-07						
	To	0.00	9.10E-07	6.46E-05	15483	8.9499E-07	6.6488E-09	7.8229E-09	2.1157E-10
Scrub 2 days	From	0.00	9.10E-07						
	To	-2.00	9.10E-07	4.37E-05	22902	8.9499E-07	6.6488E-09	7.8229E-09	2.1157E-10
Flight	From	0.00	1.03E-09						
	To	-12.00	1.03E-09	2.96E-07	3383365	7.6406E-10	1.4908E-11	3.5727E-11	2.1157E-10

Note: Once the vehicle reaches Orbit, the COPV risk is gone.

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Mitigating Buckling Concerns

Analysis of Potential for Titanium Liner Buckling after Proof in a Large Kevlar/Epoxy COPV, AIAA 2009-2520

COPV – Suspect Buckling

- **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**

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Borescope Photographs

Experimentally Observed Surface Depressions
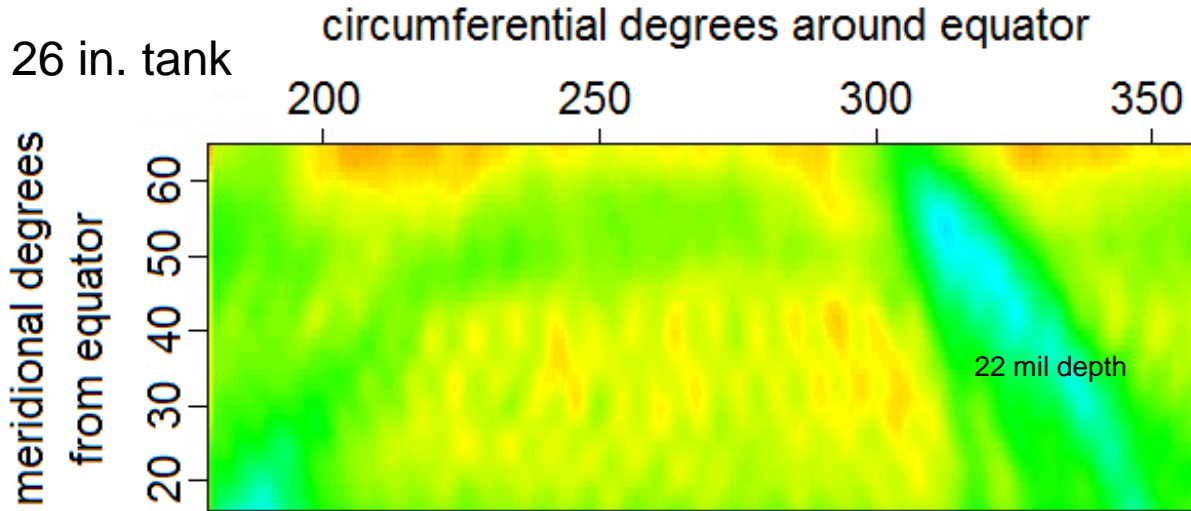
26 in. tank
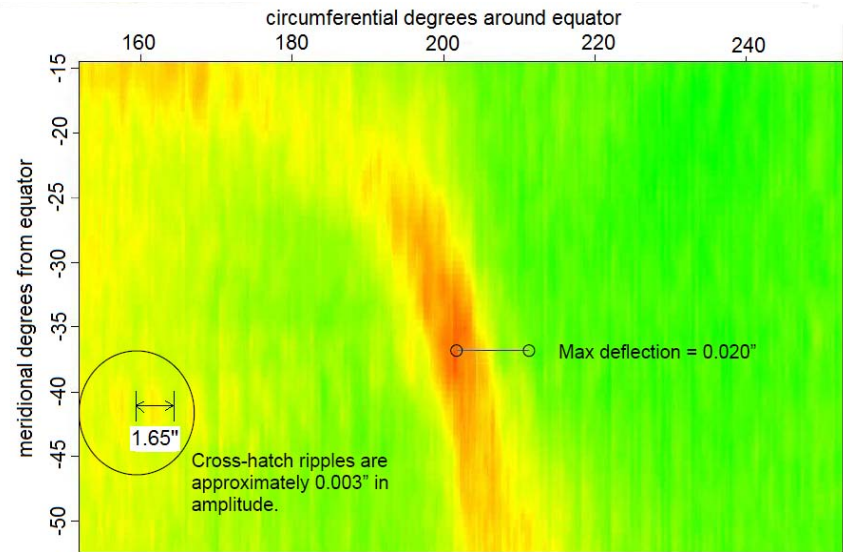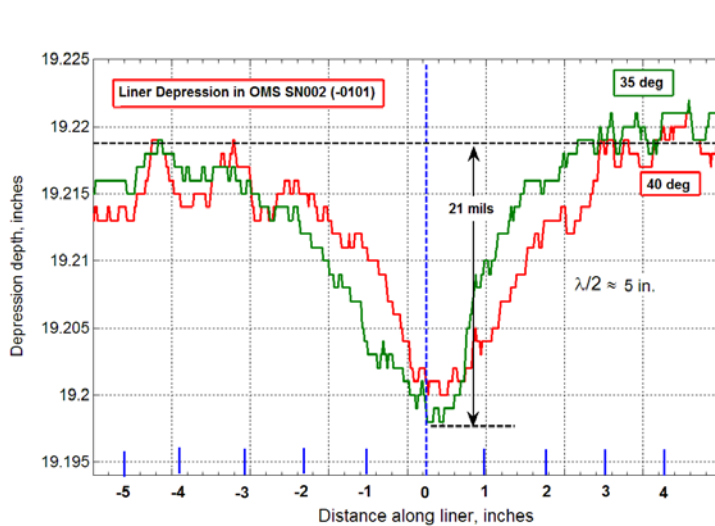
Cross-Section of Surface Depressions

40 in. tank

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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.**
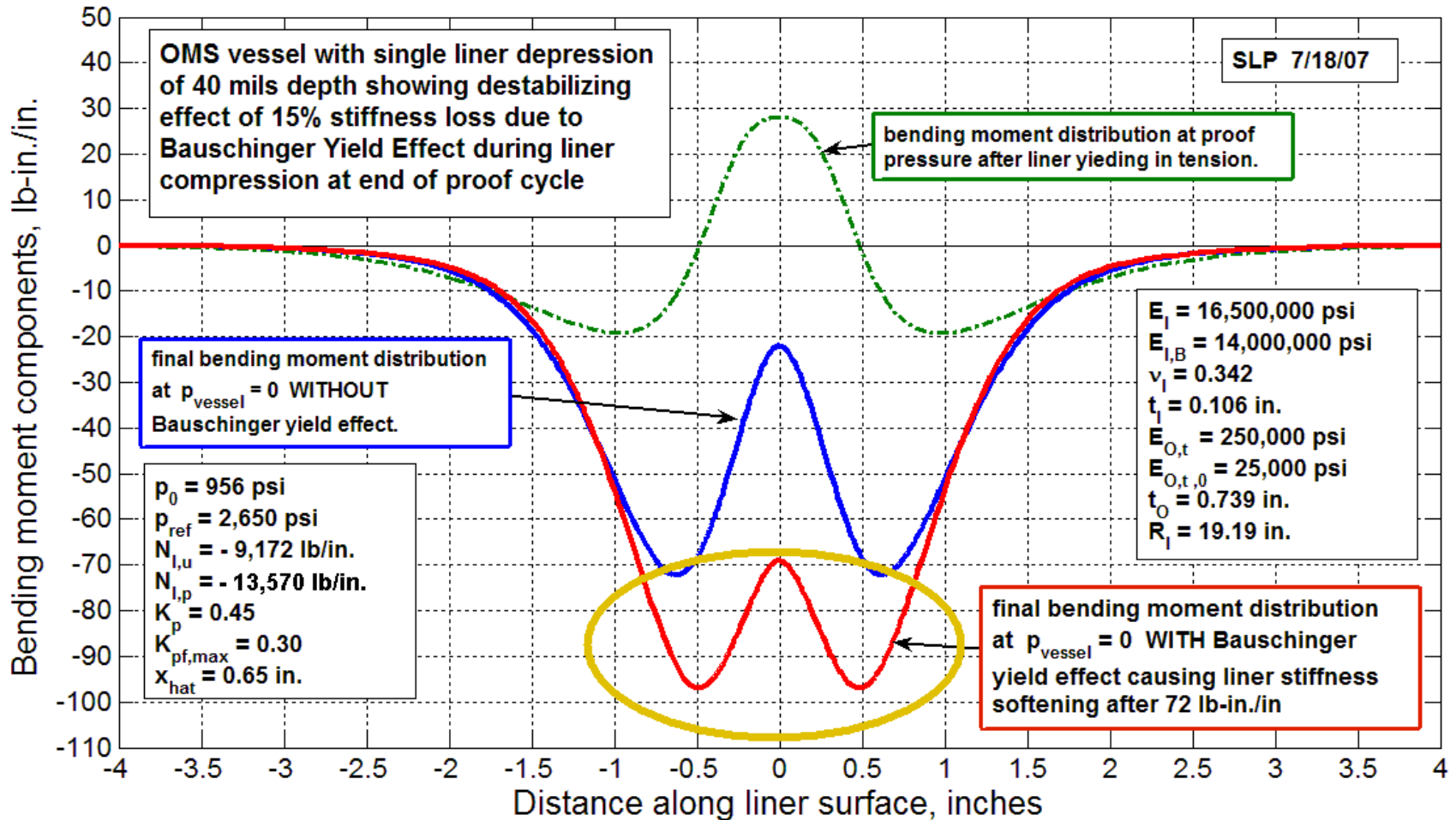
Bauschinger Effect from Yielding

Uniaxial load cycles applied to a specimen taken from a Ti liner demonstrating the Bauschinger effect
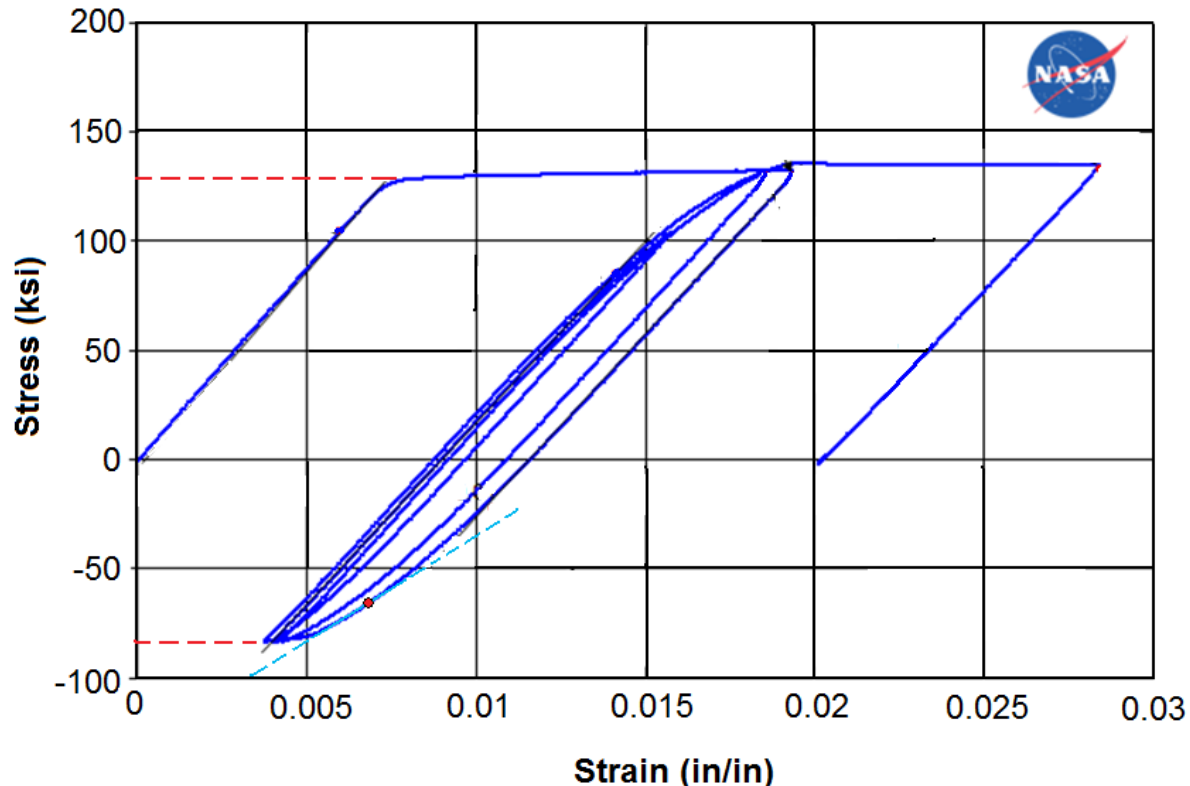
Material response in tension differs than in compression. Bauschinger effect becomes key in developing instability wherein extensive prior yielding in tension reduces the magnitude of the yield threshold in compression by 30 to 40% compared to the virgin annealed state of the titanium.
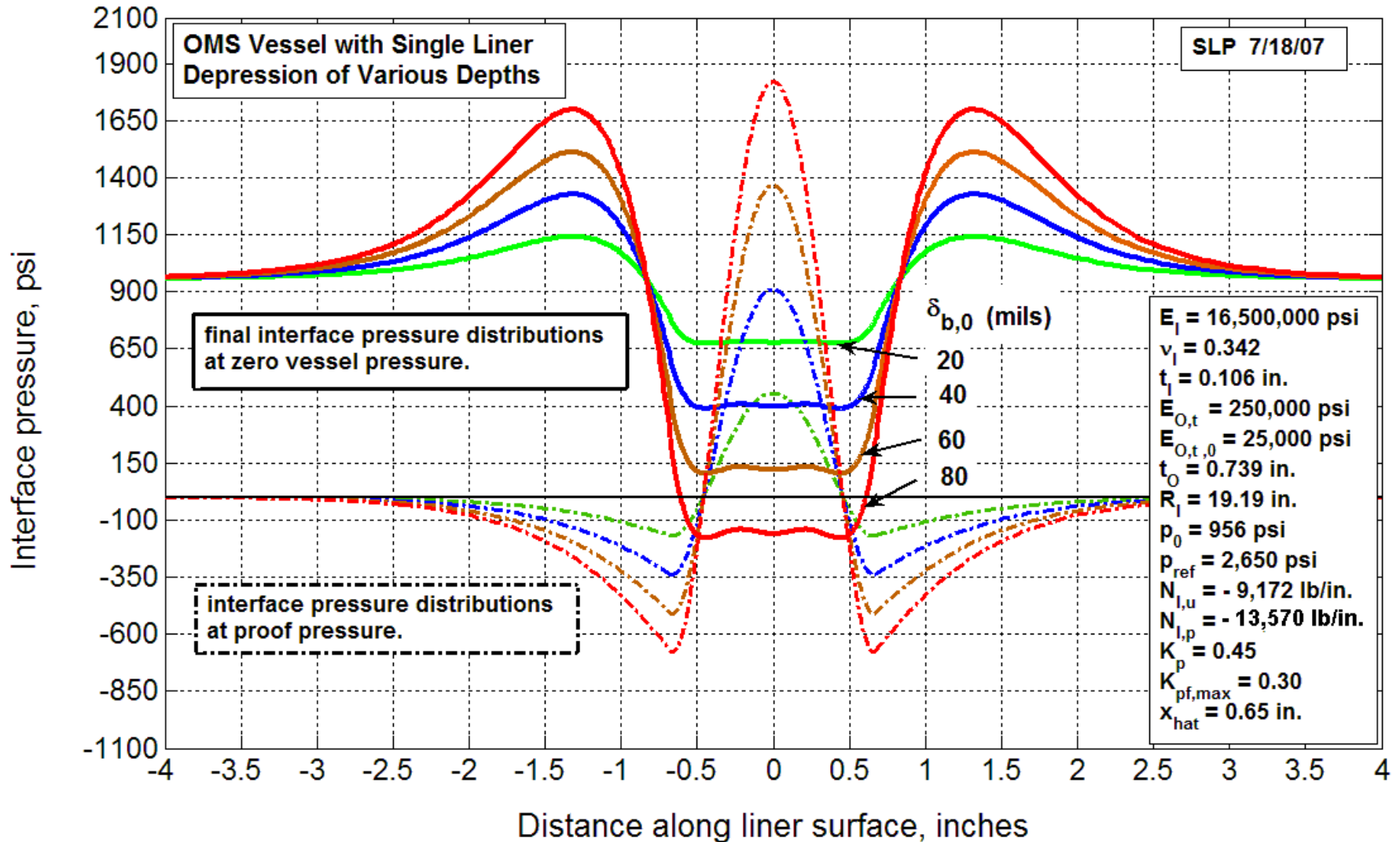
48

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

SLP 7/18/07

bending moment distribution at proof pressure after liner yieding in tension.

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

$E_I = 16,500,000$ psi
$E_{I,B} = 14,000,000$ psi
$\nu_I = 0.342$
$t_I = 0.106$ in.
$E_{O,t} = 250,000$ psi
$E_{O,t,0} = 25,000$ psi
$t_O = 0.739$ in.
$R_I = 19.19$ in.

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

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

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Effect Changing Depression Depth on Interface Pressure

Effect Changing Depression Depth on Bending Moment

51
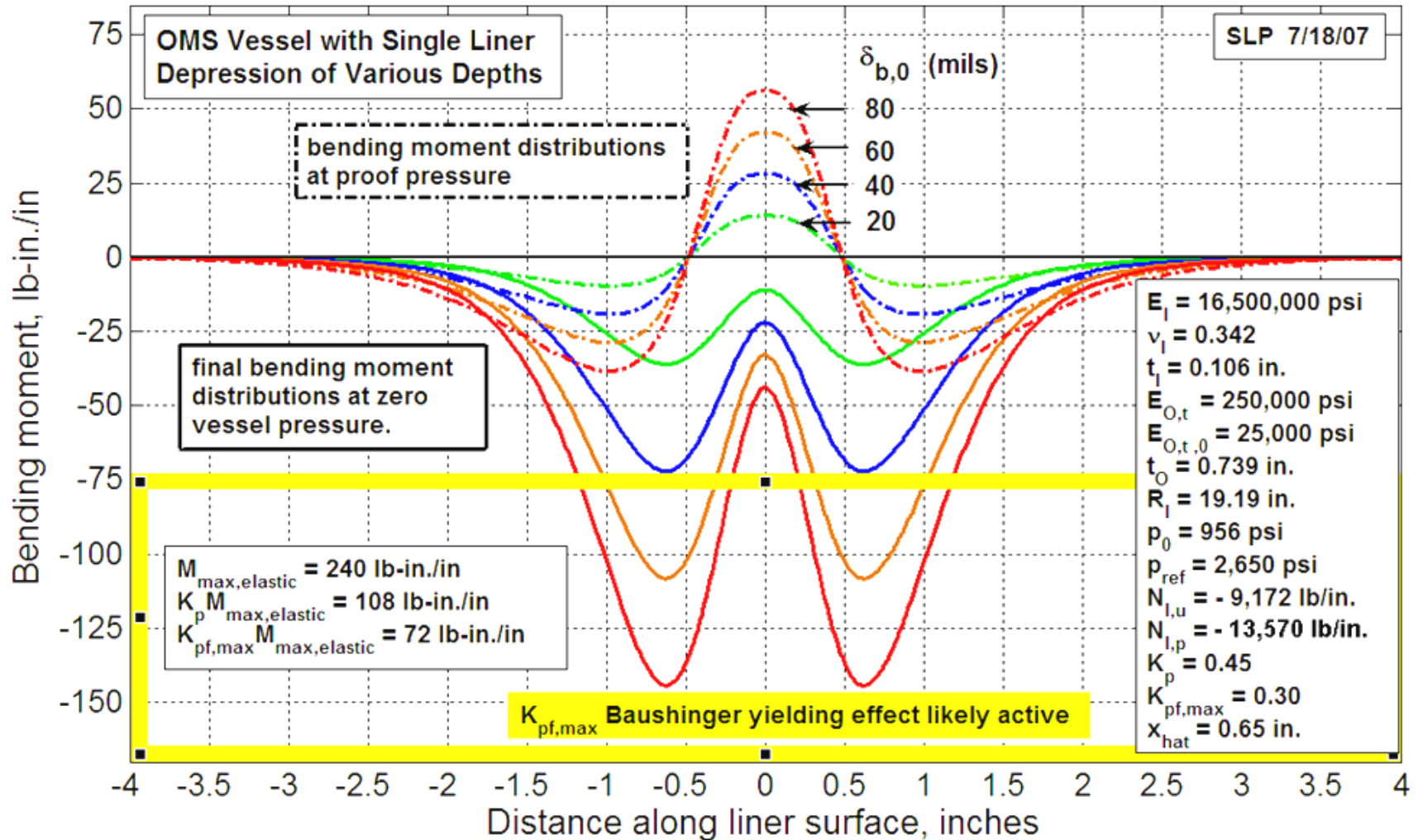
Conclusions

- **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 160ºF (Phase 3)**
    - **Pressure, Temperature: 5400 psia, at 173ºF (Phase 4)**

Accelerated Stress Rupture Test

Test article eventually failed after 3,100,000 effective hours

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Bayes Analysis

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

Statistical Approach to Evaluating ASRT Result

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
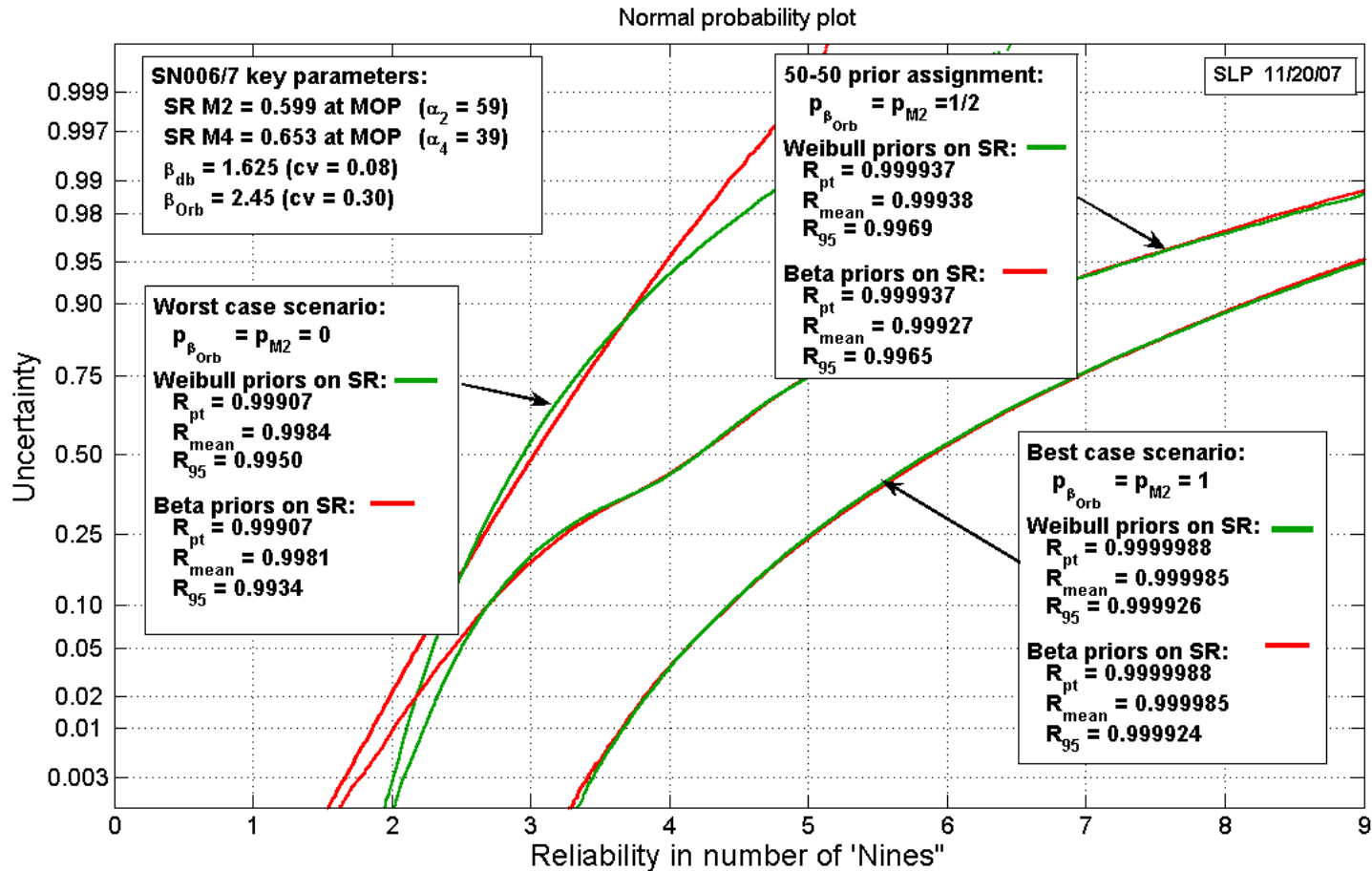
Uncertainty as a function of reliability for the different Stress Ratio Models.
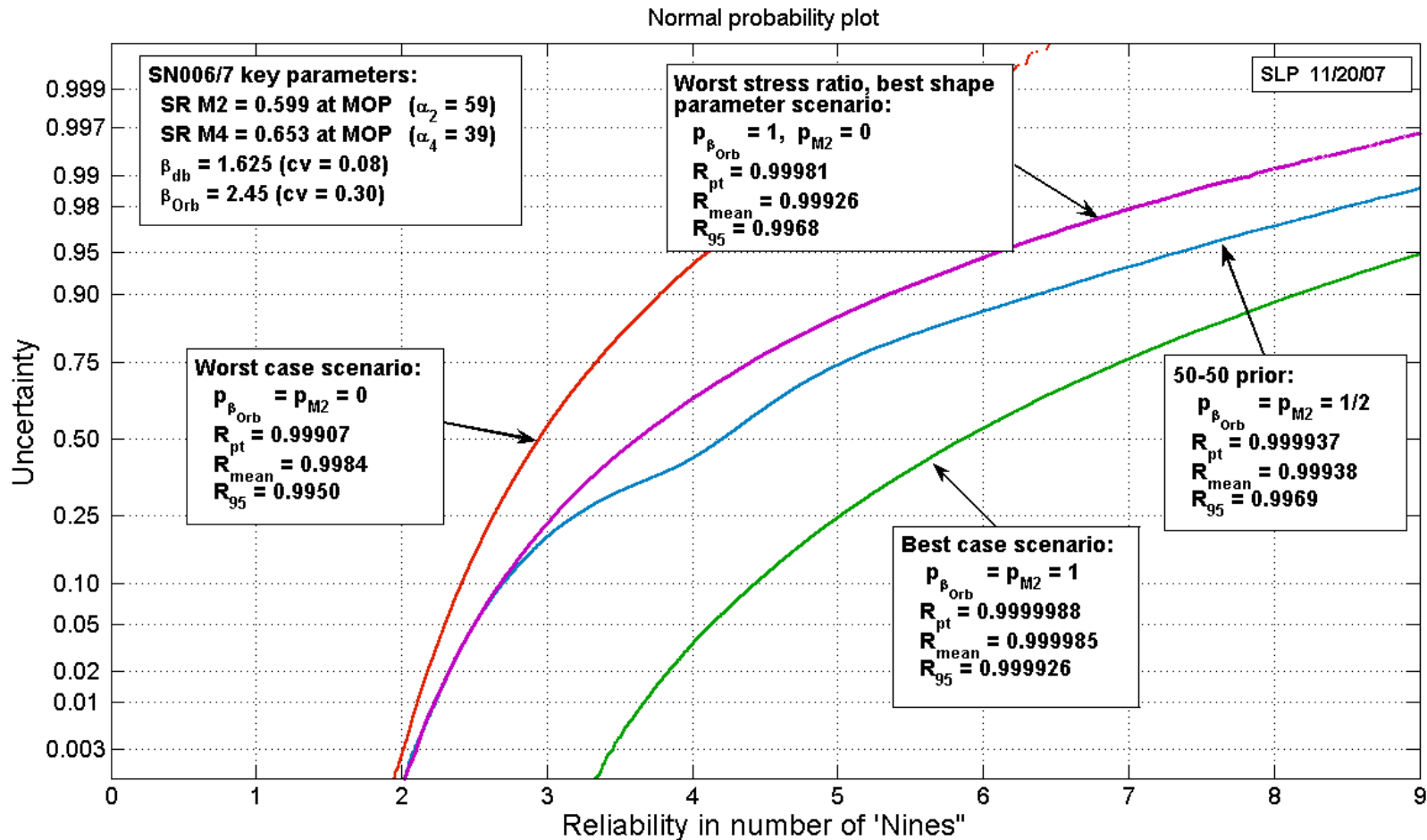
Normal probability plot

- **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).**

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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.

Raman Spectroscopy: Potential NDE Technique

Potential technique to assess COPV health through Non Destructive Evaluation (NDE) Techniques.
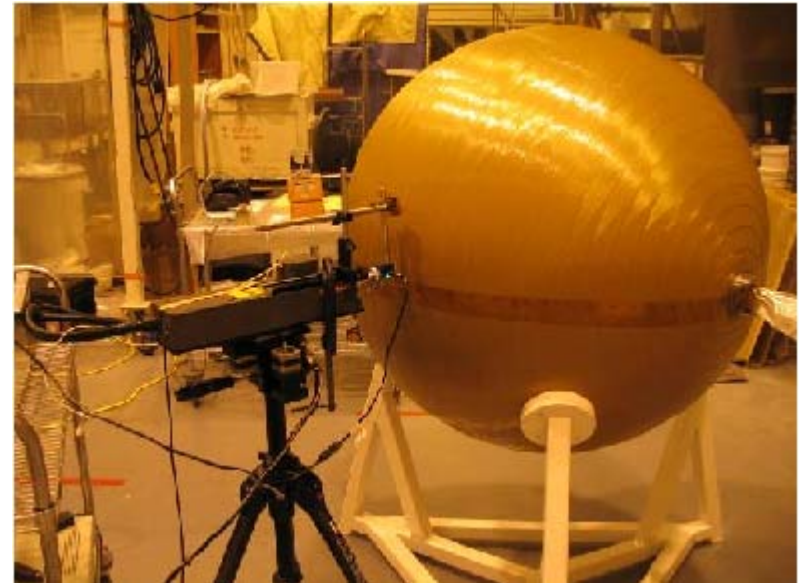
Instead of estimating the stress from the change in tank volume, hypothesis is to measure the strain using a Raman Spectrometer on the exterior of the tank and correlate to stress through the thickness of the overwrap.   (Nobel Prize 1930)

Kaiser Measurements: SN001
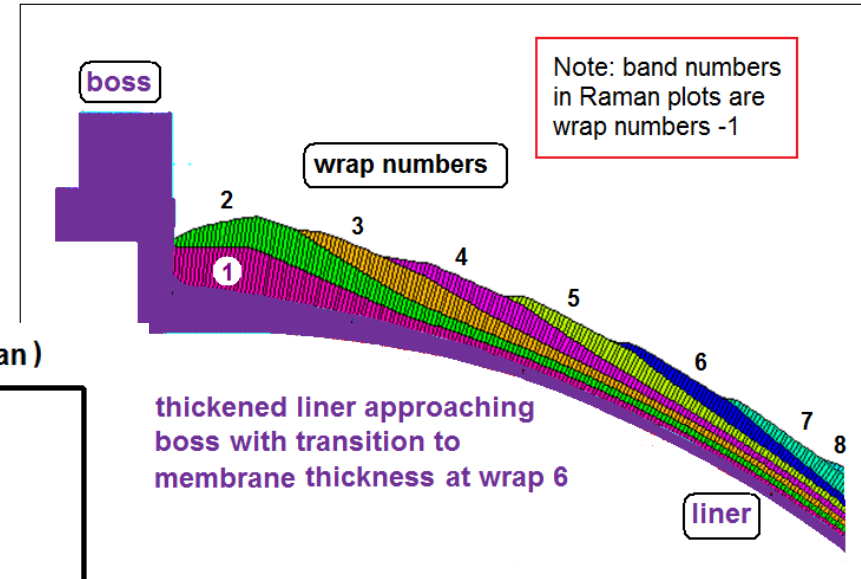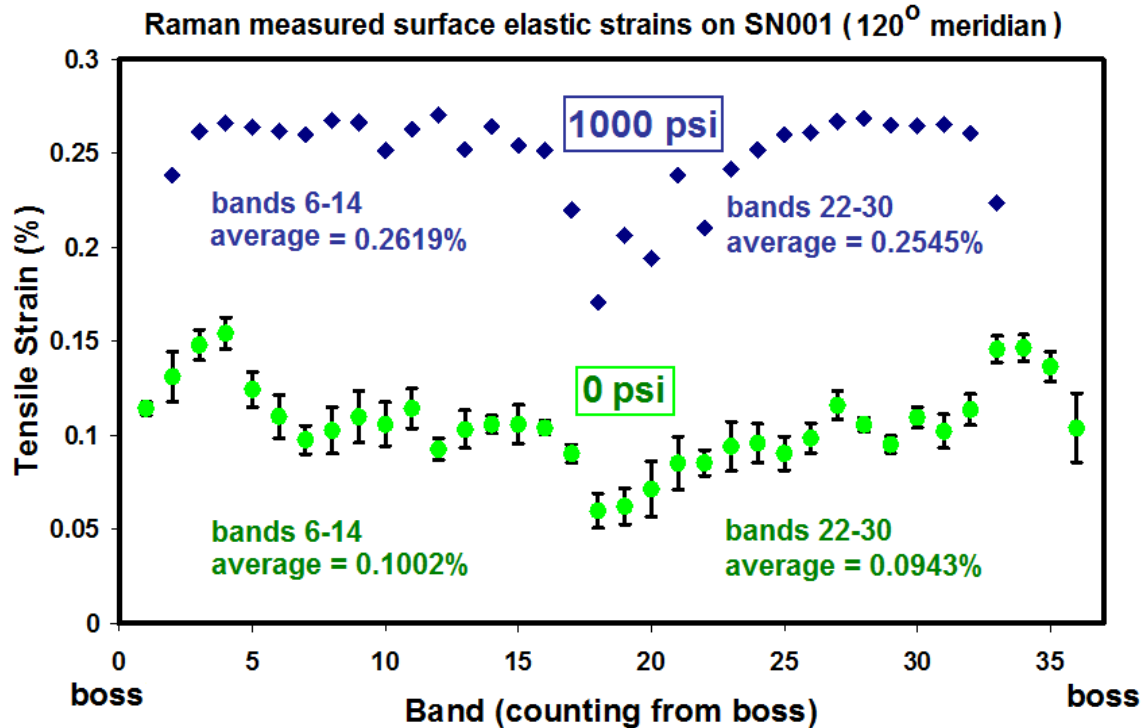
Measurements have precision to distinguish different wraps.

63
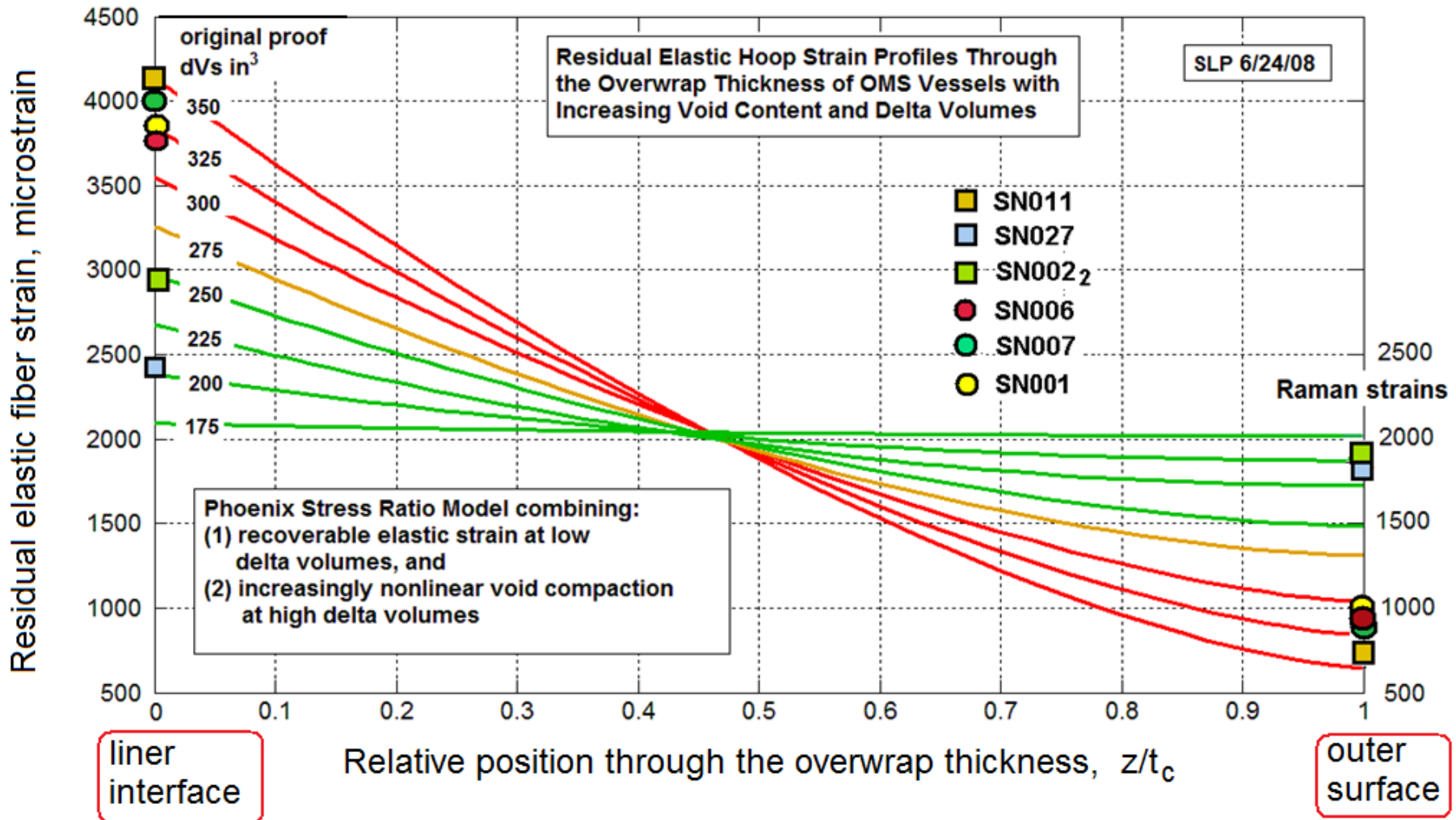
Raman as an NDE Technique

65
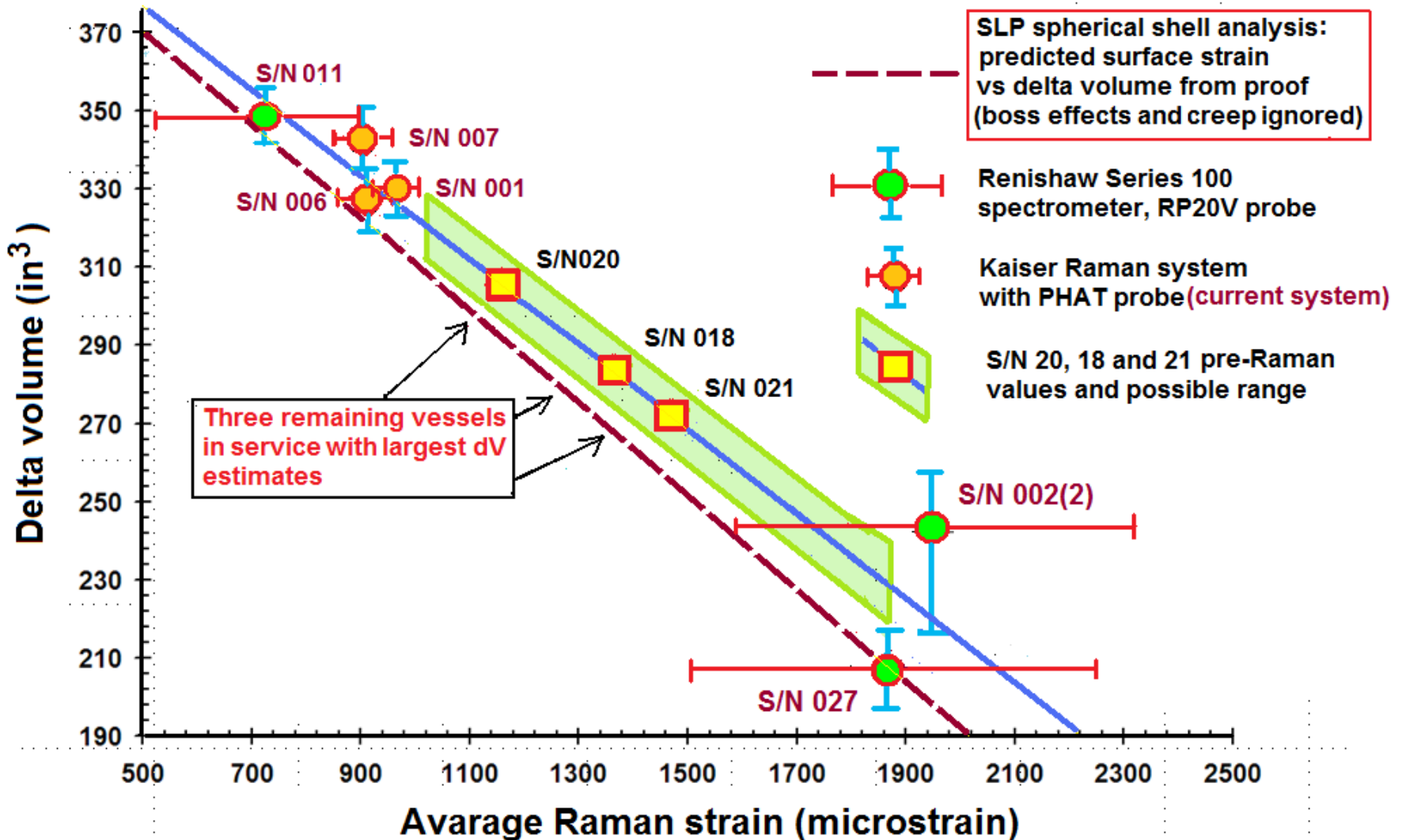
Relook at Reliability

Lognormal plot
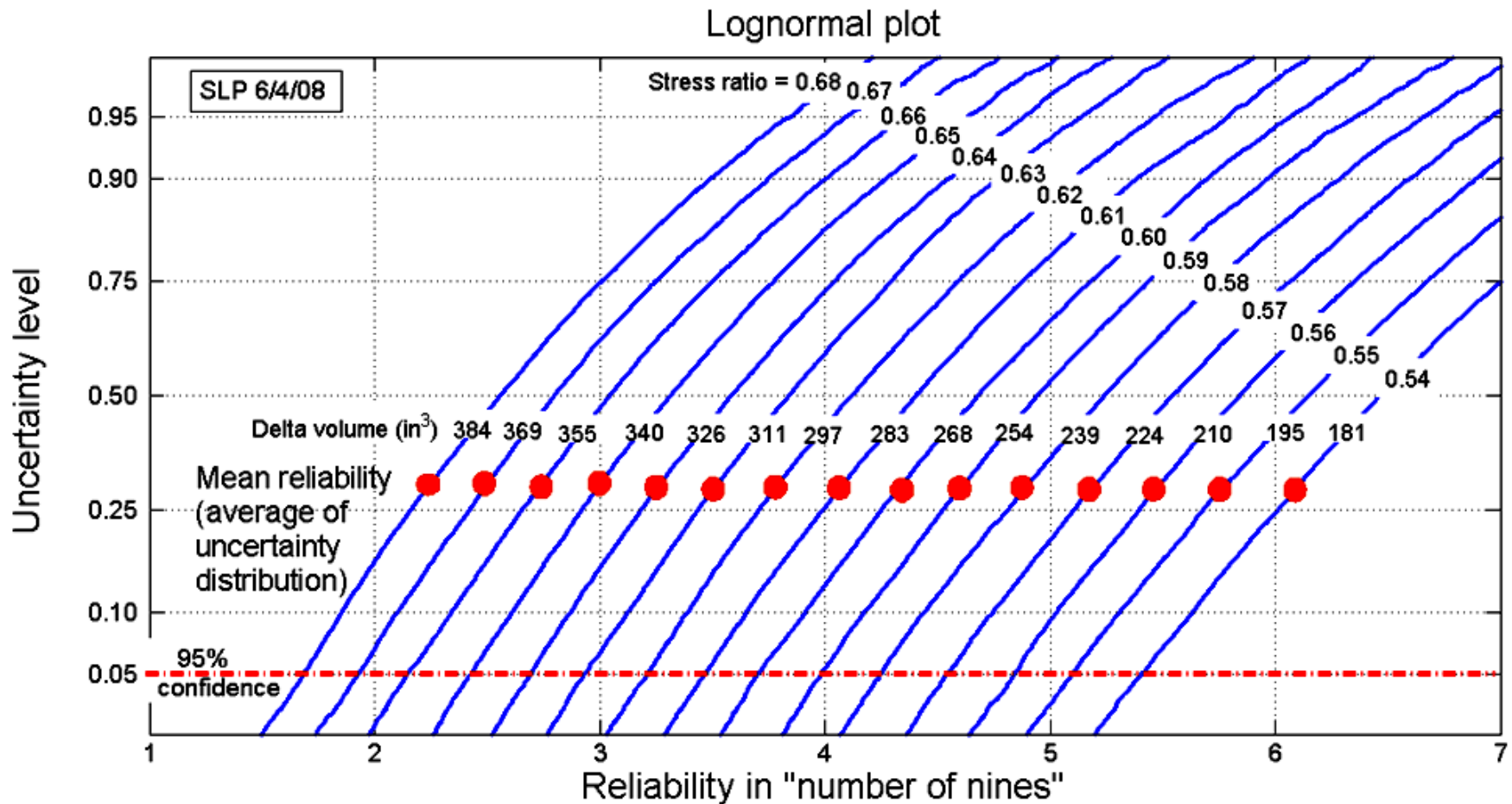
SN020 – currently carried as 310 in³. Would Raman measurements change current risk level? update reliability to two 9's or four 9's?

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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**

COPV	Geometry	Media	Volume	On-Orbit Maximum Fill Pressure	Maximum Design Operating Pressure	Minimum Design Burst Pressure	Fill/Burst Pressure Ratio	Approx Design Safety Factor
	(in.)		(in^3)		(psig)			
HPGT	37.89 Ø	O_2 or N_2	26,093	2509	3400	6800	0.369	2.71:1
NTA	45 L x 19.7 Ø	N_2	12,000	2495	3000	6000	0.416	2.41:1
PCU	15.37 Ø	Xe	1680	1400	3000	6000	0.233	4.29:1
SAFER	9 L x 6 Ø	N_2	170	8000	10000	20000	0.400	2.5:1
VGA	7.22 L x 3.55 Ø	Air	44.6	1500	3000	6000	0.250	4:1
GBA	17.1 L x 8.5 Ø	Ar	655	2630	3000	6000	0.438	2.28:1
AMS-2-Xe	15.37 Ø	Xe	1680	2500	3000	6000	0.417	2.4:1
AMS-2-CO_2	12.4 Ø	CO_2	813	1440	3200	6400	0.225	4.44:1
AMS-2-He	21.7 L x 6.6 Ø	He	505	2900	3538	8845	0.328	3.05:1
VCAM	8.1 L x 3.68 Ø	He	47.8	1985	2150	15300	0.130	7.71:1
GBU-Ar	9.8 Ø	Ar	467	1987	2630	5260	0.378	2.65:1
GBU-He	9.8 Ø	He	467	1987	2630	5260	0.378	2.65:1
GBU-CO_2	9.8 Ø	CO_2	467	435	2630	5260	0.083	12.1:1

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
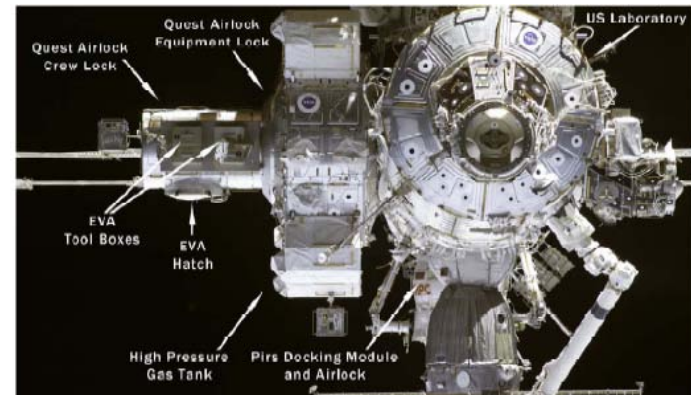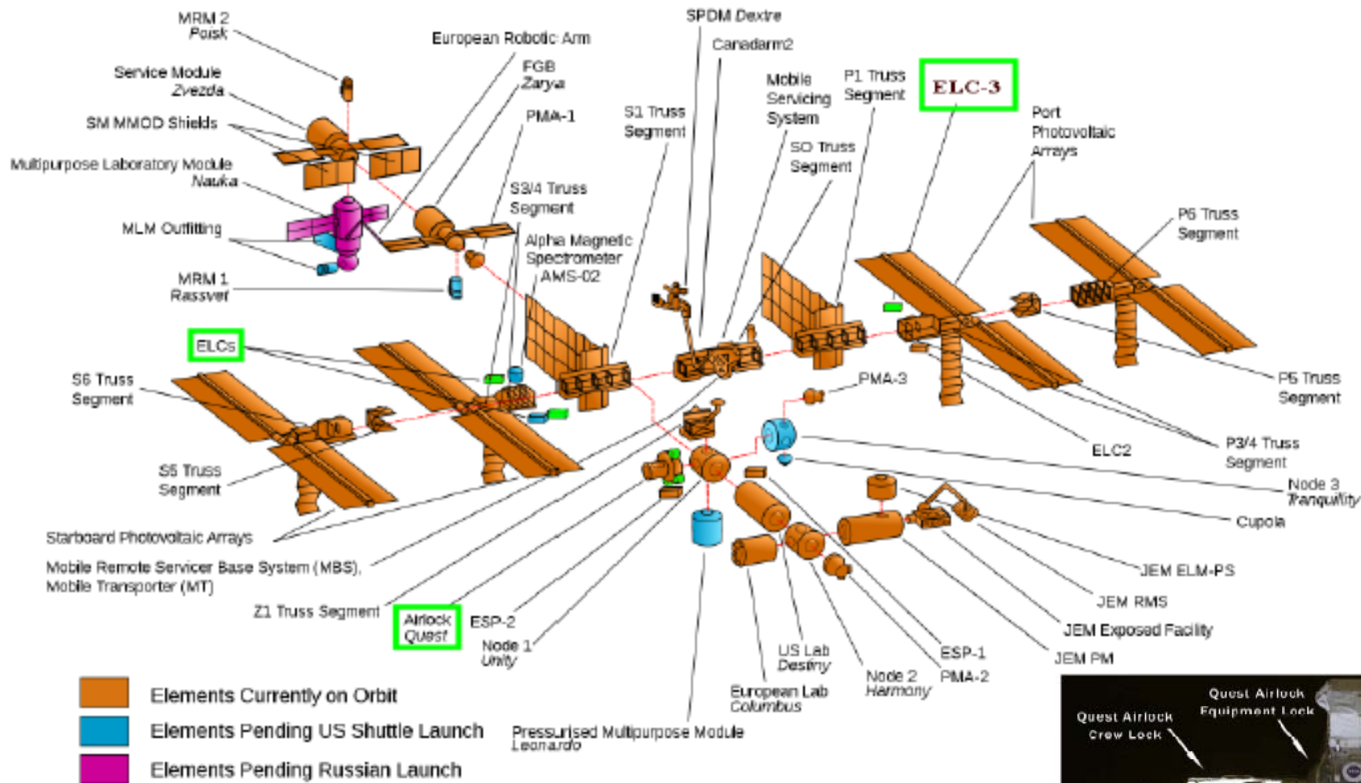
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Nitrogen Oxygen Recharge System:

Shuttle currently supplies gasses to ISS

Post Shuttle Retirement COPVs will deliver O2 and N2.

Backup Charts