Composite Overwrapped Pressure Vessels (COPV) Stress Rupture Test
Part 2

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One of the major concerns for the aging Space Shuttle fleet is the stress rupture life of composite overwrapped pressure vessels (COPVs). Stress rupture life of a COPV has been defined as the minimum time during which the composite maintains structural integrity considering the combined effects of stress levels and time.

To assist in the evaluation of the aging COPVs in the Orbiter fleet an analytical reliability model was developed. The actual data used to construct this model was from testing of COPVs constructed of similar, but not exactly same materials and pressure cycles as used on Orbiter vessels.

Since no actual Orbiter COPV stress rupture data exists the Space Shuttle Program decided to run a stress rupture test to compare to model predictions. Due to availability of spares, the testing was unfortunately limited to one 40" vessel.

The stress rupture test was performed at maximum operating pressure at an elevated temperature to accelerate aging. The test was performed in two phases. The first phase, 130°F, a moderately accelerated test designed to achieve the midpoint of the model predicted point reliability. A more aggressive second phase, performed at 160°F, was designed to determine if the test article will exceed the 95% confidence interval of the model. In phase 3, the vessel pressure was increased to above maximum operating pressure while maintaining the phase 2 temperature. After reaching enough effectives hours to reach the 99.99% confidence level of the model phase 4 testing began when the temperature was increased to greater than 170°F. The vessel was maintained at phase 4 conditions until it failed after over 3 million effect hours.

This paper will discuss the results of this test, it's implications and possible follow-on testing.

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Composite Overwrapped Pressure Vessels (COPV) Stress Rupture Test Part 2

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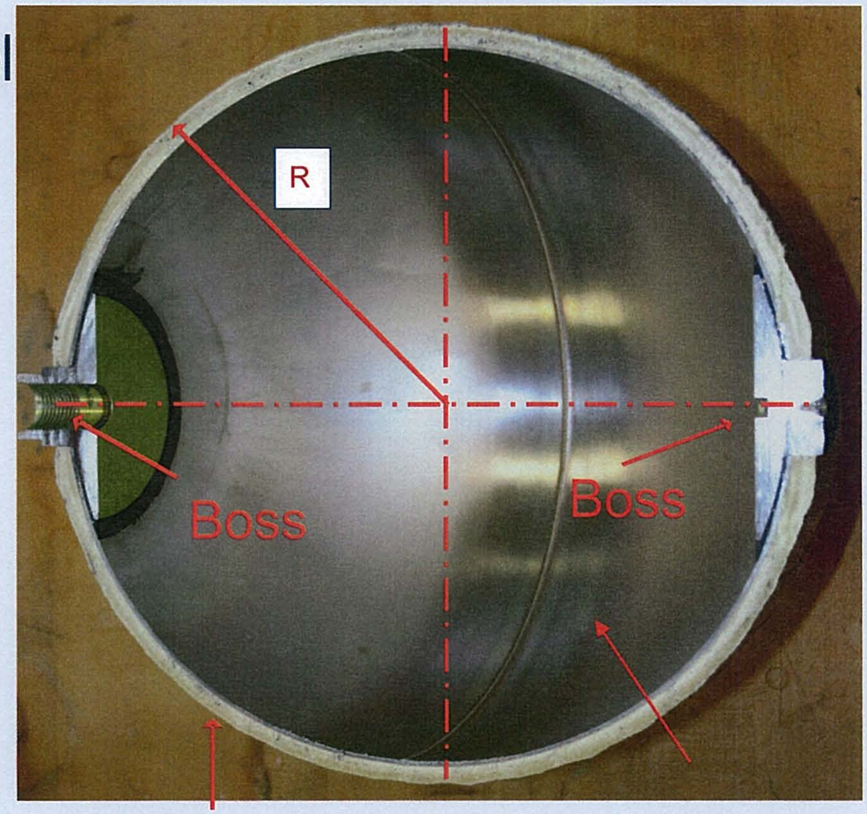
What is a COPV?

- NASA Orbiter Pressure Vessel
- Need was a light weight high strength pressure vessel
- NASA COPV was designed in 1970's
- Basic Composition:
  - Boss
  - Composite Overwrap
  - Metallic Liner
- Safety is key factor



Composite Overwrap

Metallic Liner

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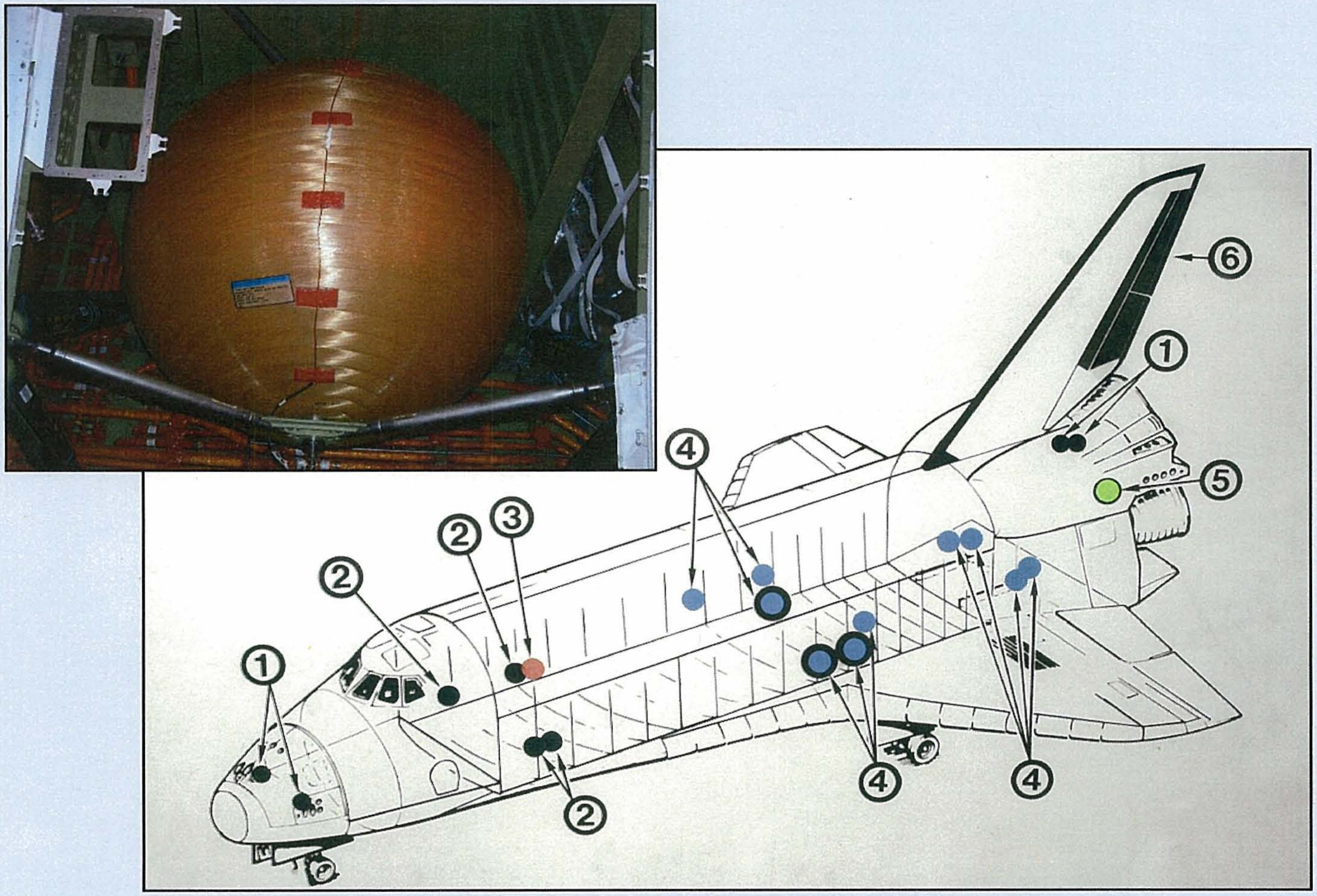
Orbiter Systems



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COPV Aging Issues

- The Space Shuttle Orbiter COPVs are operating outside their designed 10 year life.
  - There are 3 mechanisms that affect the life of a COPV
    - Age life of the overwrap (addressed at Aging Aircraft 2008)
    - Cyclic fatigue of the metallic liner
    - Stress Rupture life

The first two mechanisms are understood through test and analysis

- A COPV Stress Rupture is a sudden and catastrophic failure of the overwrap while holding at a stress level below the ultimate strength for an extended time.

- Currently there is no simple method of determining the stress rupture life of a COPV nor a screening technique to determine if a particular COPV is close to the time of a stress rupture failure.

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Stress Rupture Reliability

- The most substantial source of data concerning COPV stress rupture was a test program conducted at LLNL involving over 100 Kevlar wrapped vessels.
  - Testing was relatively uncontrolled, leading to inconclusive results
- Considerable review of all the available COPV stress rupture data was used to develop a stress rupture reliability model
- The model uses the specific characteristics of each individual COPV to predicts its stress rupture reliability
  - Survived time at MOP
  - Expected time at MOP for next or future usage
  - Stress Ratio
  - Model parameters derived from COPV test data
- The stress rupture reliability model predicts Orbiter is flying with a mean reliability of greater than 0.999 per flight and greater than 0.99 for the remainder of the Space Shuttle Program.

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Stress Ratio

- A key factor in the stress reliability model is the Stress Ratio

$$\text{STRESS RATIO} = \frac{\text{Stress in Overwrap @ MEOP}}{\text{Stress in Overwrap @ Burst}}$$

  - The stress at burst varies from vessel to vessel, therefore the discrete stress rupture varies from vessel to vessel

- Stress ratio curves were developed in a conservative matter using test results from several Orbiter COPVs
  - "Older" MPTA COPV
    - Several cycles to MOP (fast and slow) followed by a burst test
  - Health check of four 40" spares

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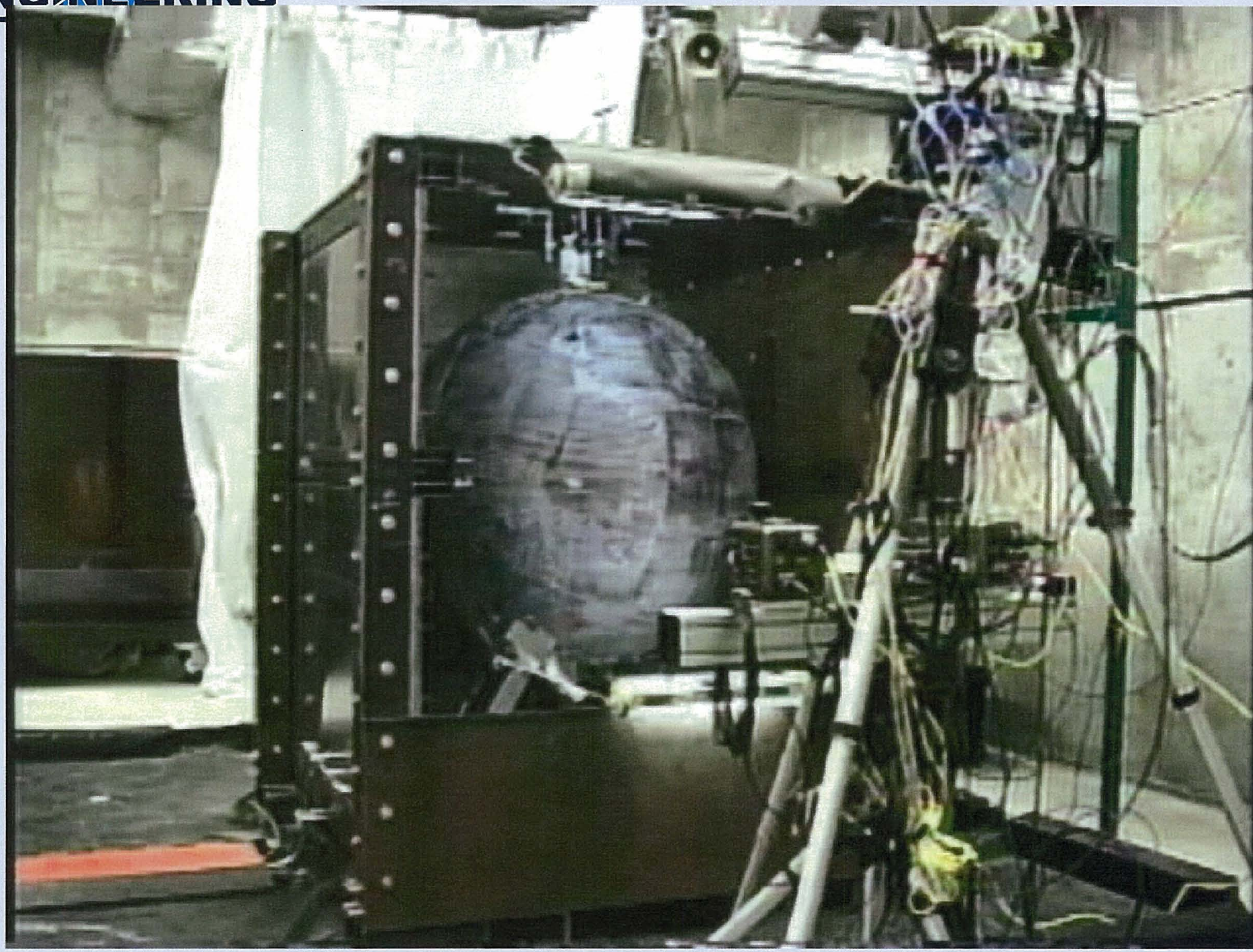
Why do a test?



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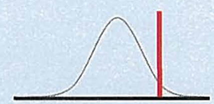
Test Objectives

- Space Shuttle Program directed a test to compare Orbiter COPV performance to the reliability model predictions because:
  - Reliability model is based on data from test articles that differ from flights COPVs
    - Manufacturing, material & pressure cycle
  - No Orbiter COPV stress rupture test data exists.
- Due to limited resources the test program was limited to a single COPV
  - A single data point will not <u>validate</u> the current model but could provide confidence in model predictions
- An accelerated test was designed
  - Selected test article removed from service and believed to be "worst flight tank"
  - Starting at maximum operating pressure of 4850 psi
  - Elevated temperature
  - Pressure and/or temperature increased in phases
  - Orbiter Project goal to reach 95% chance of failure



Reliability

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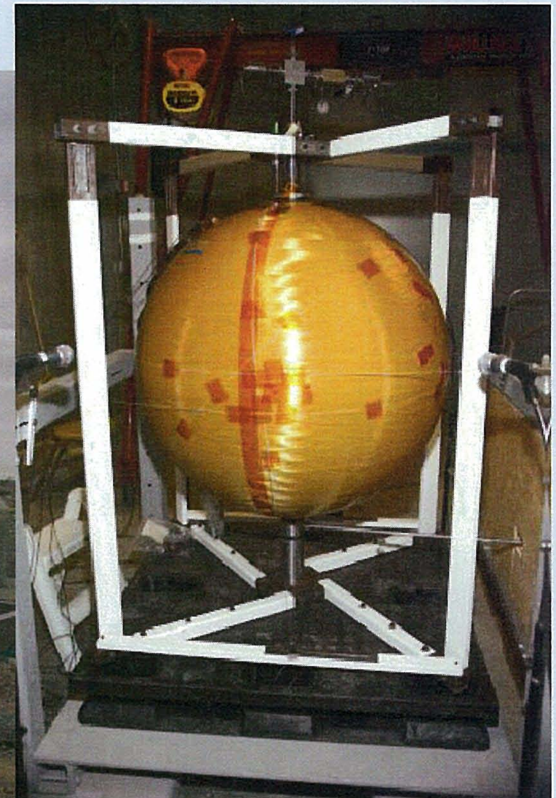
Test Cell and Test Article



OMS/RCS test article in test frame. Allows freedom of movement to monitor vessel dimensional changes during test.

WSTF Test Cell, thermally controlled test cell with generator back-up. Precludes thermal control concerns akin to those of the LLNL tests.

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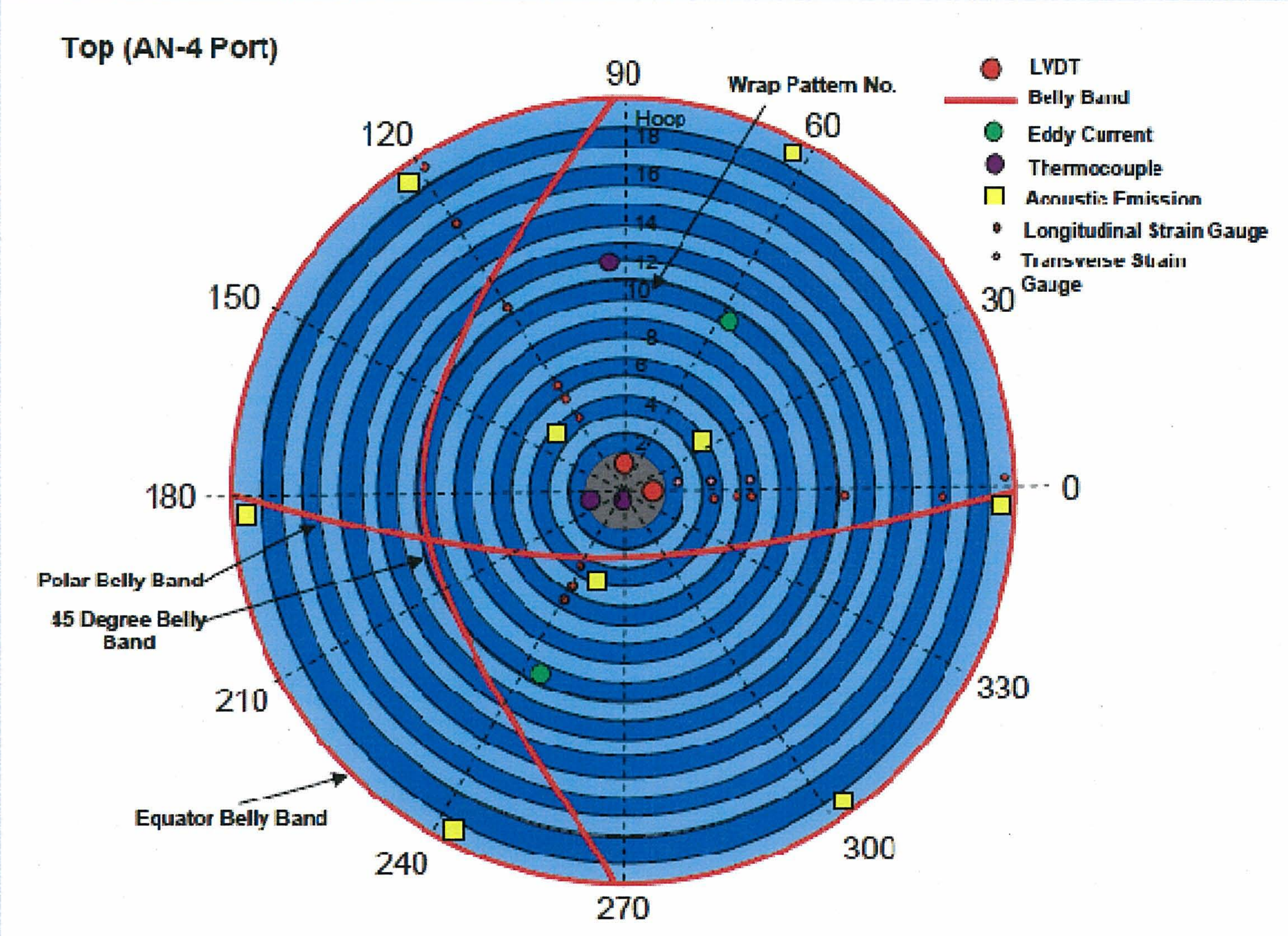
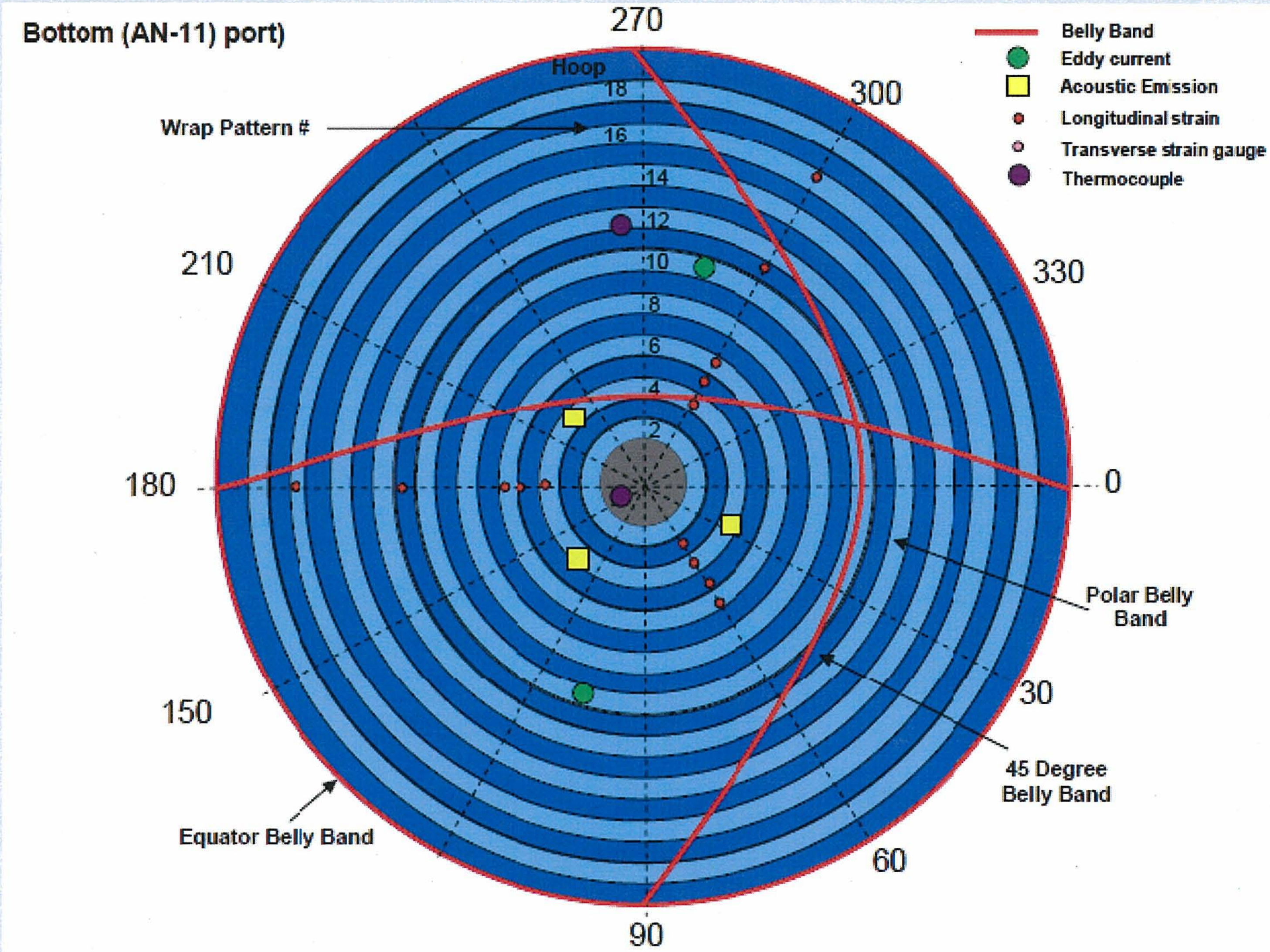
Key Instrumentation

Test/Measurement	Purpose
Fluid Temperature	Test control parameter
Fluid Pressure	Test control parameter
Belly Bands	External diameter measurement
Acoustic Emission	Pinpoint failure location (triangulate)
Strain Gauges	Outer surface strain
Axial LVDT	Boss-to-boss growth
Eddy Current	Through wall thickness change
Video/Audio	Test documentation
Raman Spectroscopy	Engineering information – NDE development for external residual stress elastic strain

Instrumentation Map - Top



Instrumentation Map - Bottom



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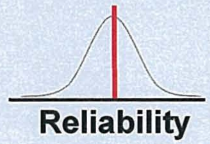
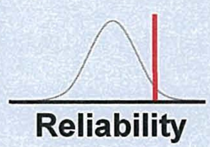
Test Program/Results

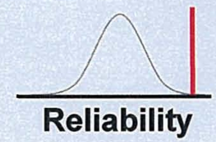
- Phase I
  - Pressure: 4850 psi
  - Temperature: 130°F
  - Time: 38,000 effective hours
  - Result: Tank passed with no issues
  - Model Prediction: 50% chance of failure



- Phase II
  - Pressure: 4850 psi
  - Temperature: 160°F
  - Time: 87,000 effective hours
  - Result: Tank passed with no issues
  - Model Prediction: 95% chance of failure



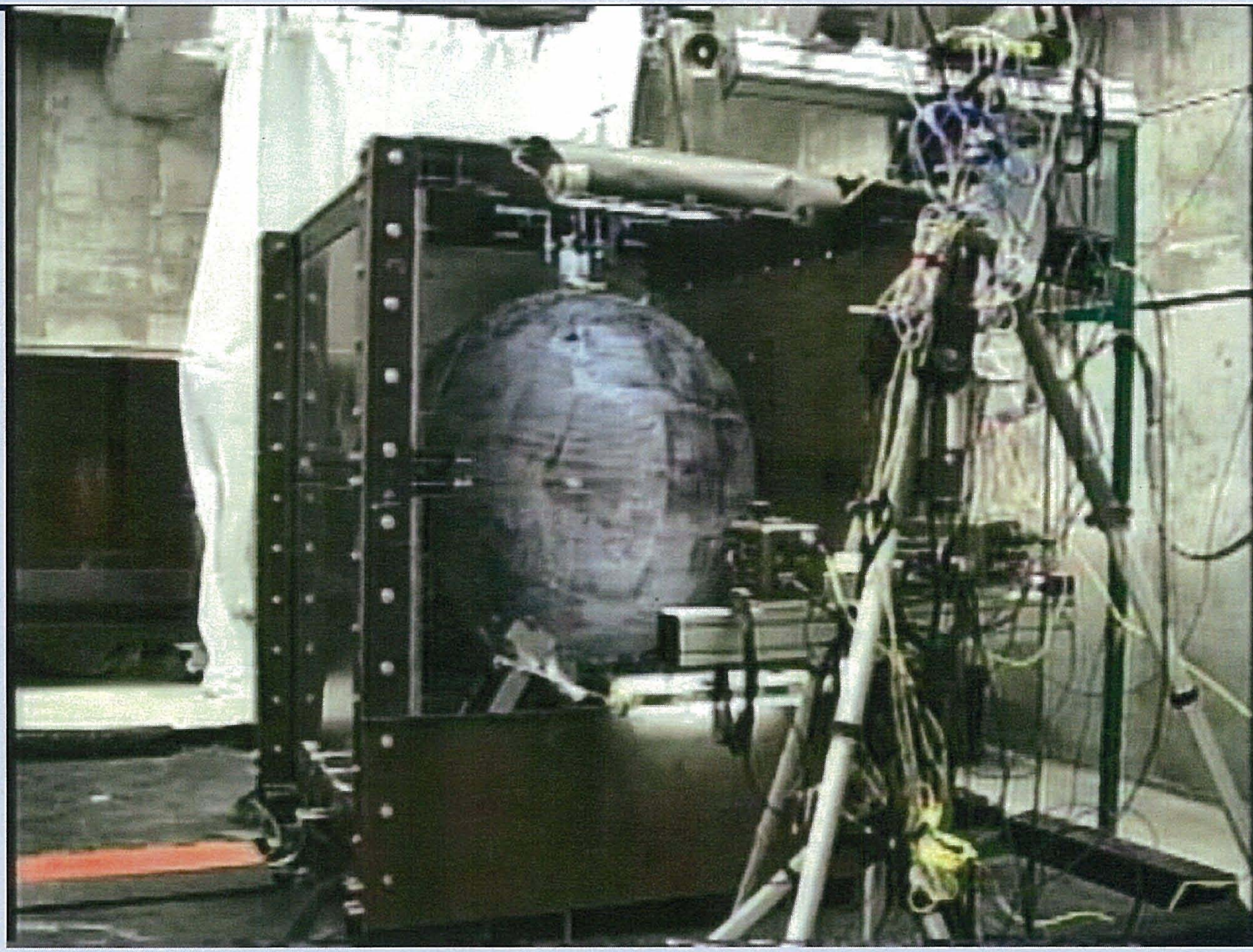
- Phase III
  - Pressure: 5200 psi
  - Temperature: 160°F
  - Time: 113,000 effective hours
  - Result: Tank passed with no issues
  - Model Prediction: 99% chance of failure



- Phase IV
  - Pressure: 5400 psi
  - Temperature: 174°F
  - Result: Tank failed after 3,100,000 effective hours

Reached Orbiter Project Objective!

Test Results



Analysis of Results

- Test was the first experimental determination of tank lifetime (industry wide)
- Testing of a flight article (exposed to space environments) proves no missed physics (confirms analysis)
- Provided best model confirmation, given validation not possible
  - Proper validation would require ~30 tanks
- Open questions
  - Was the "worst flight tank" the best test article?
    - Energizer bunny or demonstration of overstatement of risk?
  - How accurate was the prediction of stress ratio?
    - Off by 20%
  - How accurate is the model?
    - Specifically Age acceleration calculations

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Failure Analysis

- A failure analysis is planned with the following objectives:

1. Confirm Stress Rupture as the failure mode
2. Compare Kevlar properties to previous aging study
3. Investigate the condition of the liner
4. Look at comparative NDE data
5. Study instrumentation for indicators for future health monitoring of COPVs