Composite Overwrapped Pressure Vessels (COPV) Stress Rupture Test

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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. The 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.

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

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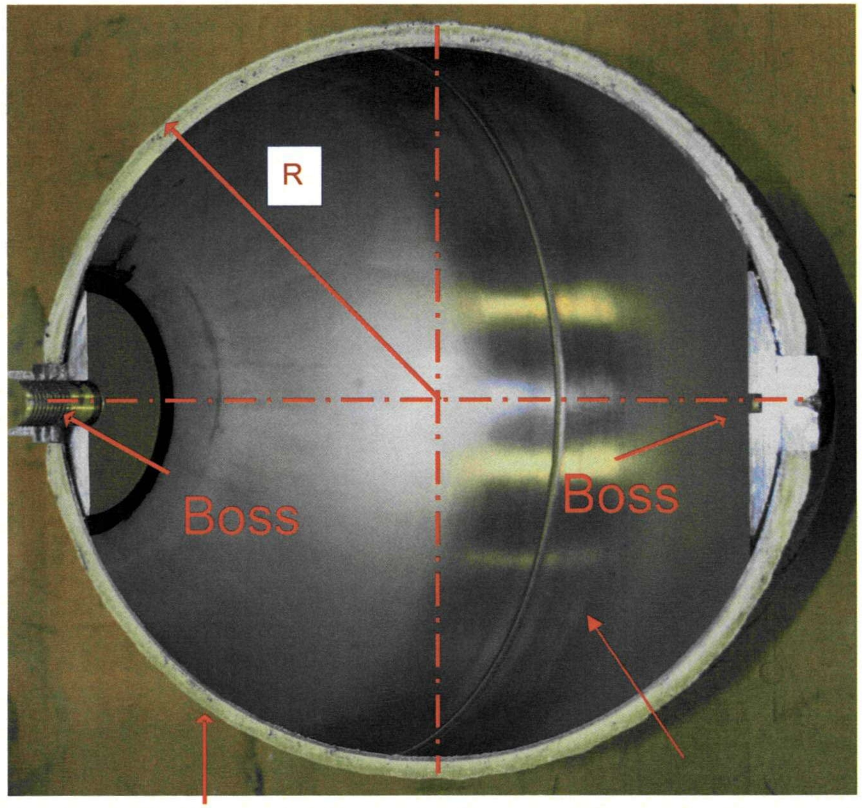
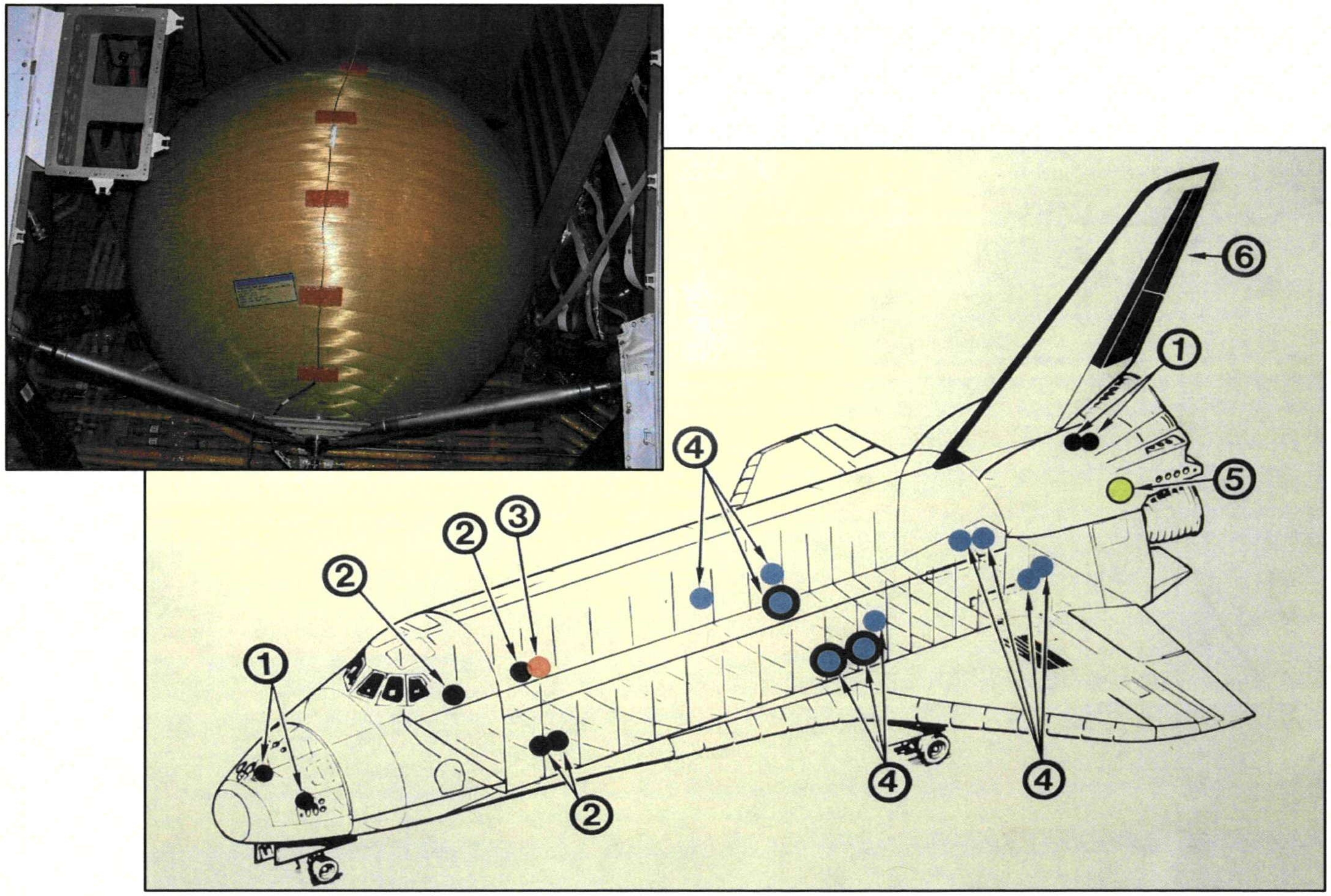
Composite Overwrapped Pressure Vessels

- 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



Space Shuttle Program

Stress Rupture

- 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.

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.

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

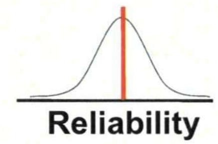
Test Objectives

- 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

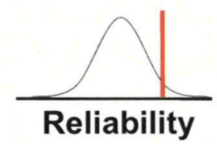
Two Phase Test Program

- The Orbiter Project Approved a Two Phase Test Program
  - Phase 1 – Moderately Accelerated



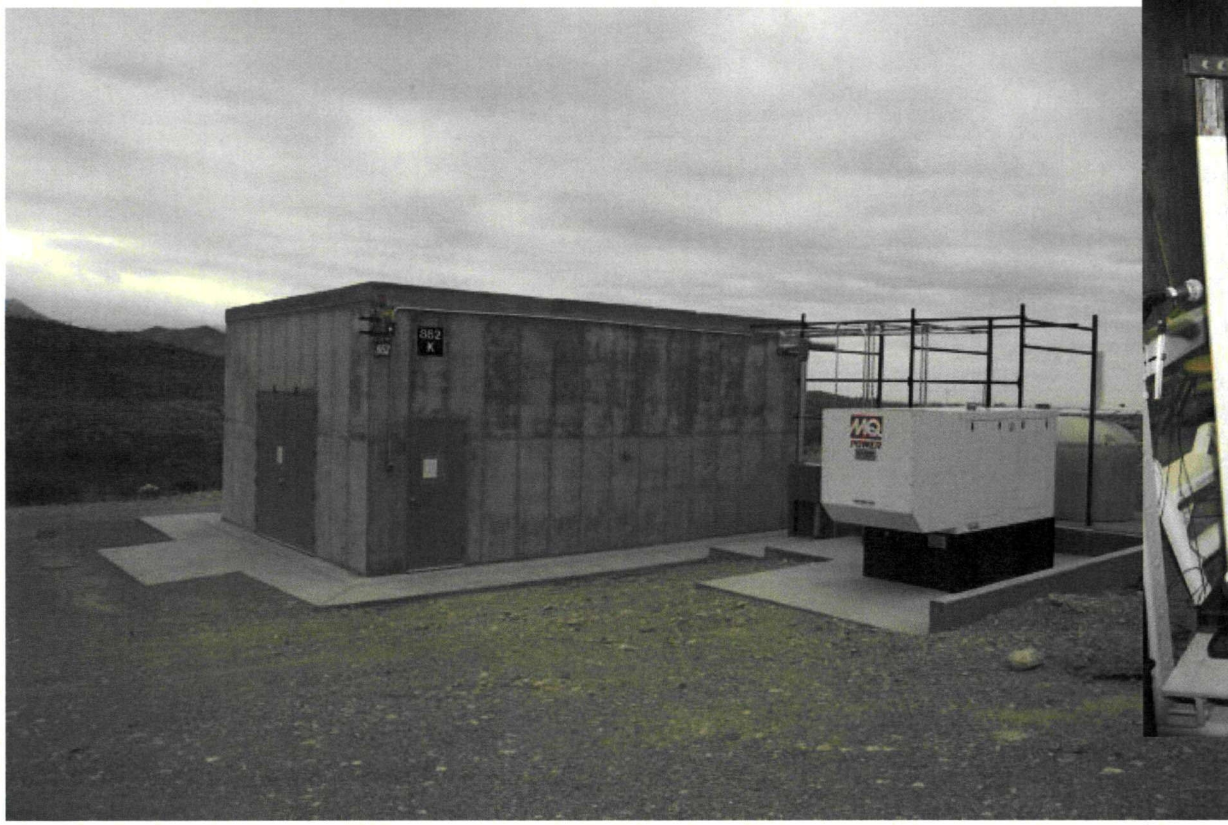
    - Achieves midpoint of model predicted reliability
    - Maintain test at fixed elevated temperature and constant maximum operating pressure
    - If the test time is reached, then would achieve the predicted mean reliability based on the calculated stress ratio

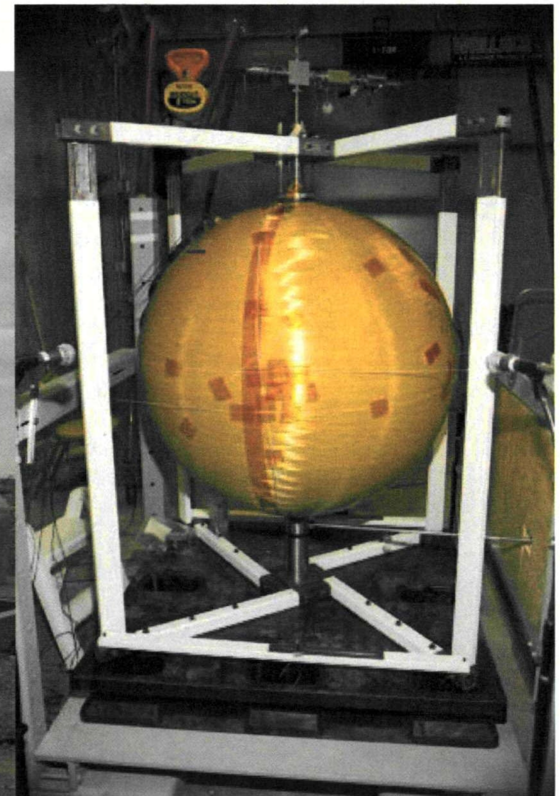
  - Phase 2 – Aggressively Accelerated



    - Gains a greater order of magnitude in reliability
    - Maintain test at fixed elevated temperature higher than phase 1 and constant maximum operating pressure
    - If the test time is reached and the model is shown to include substantial conservatism, then we would be able to update the reliability model and increase the corresponding calculated end of Program reliability.

Test Cell & Test Article





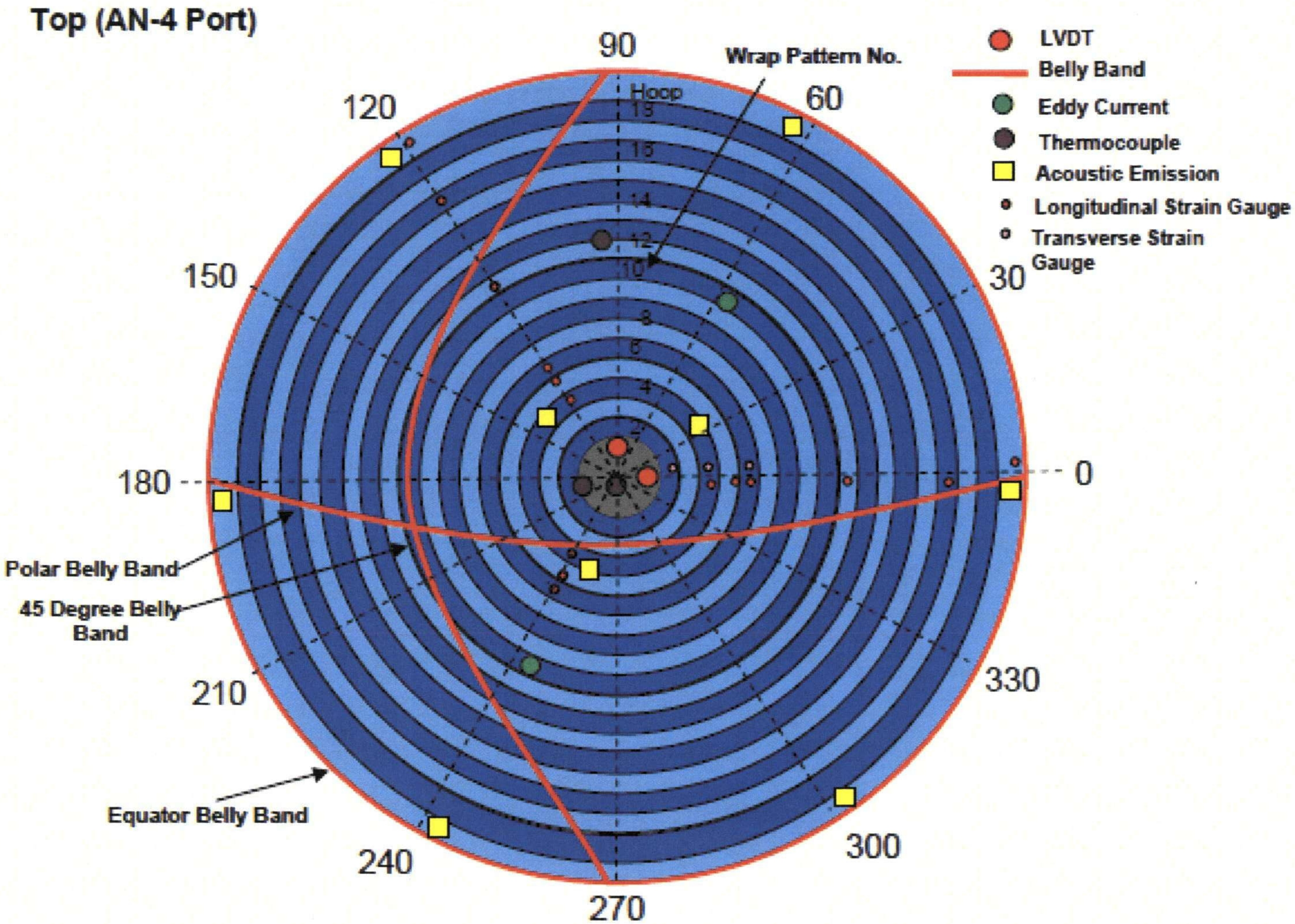
OMS/RCS test article in test frame. Allows freedom of movement to monitor vessel dimensional changes during test.

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

Key Instrumentation

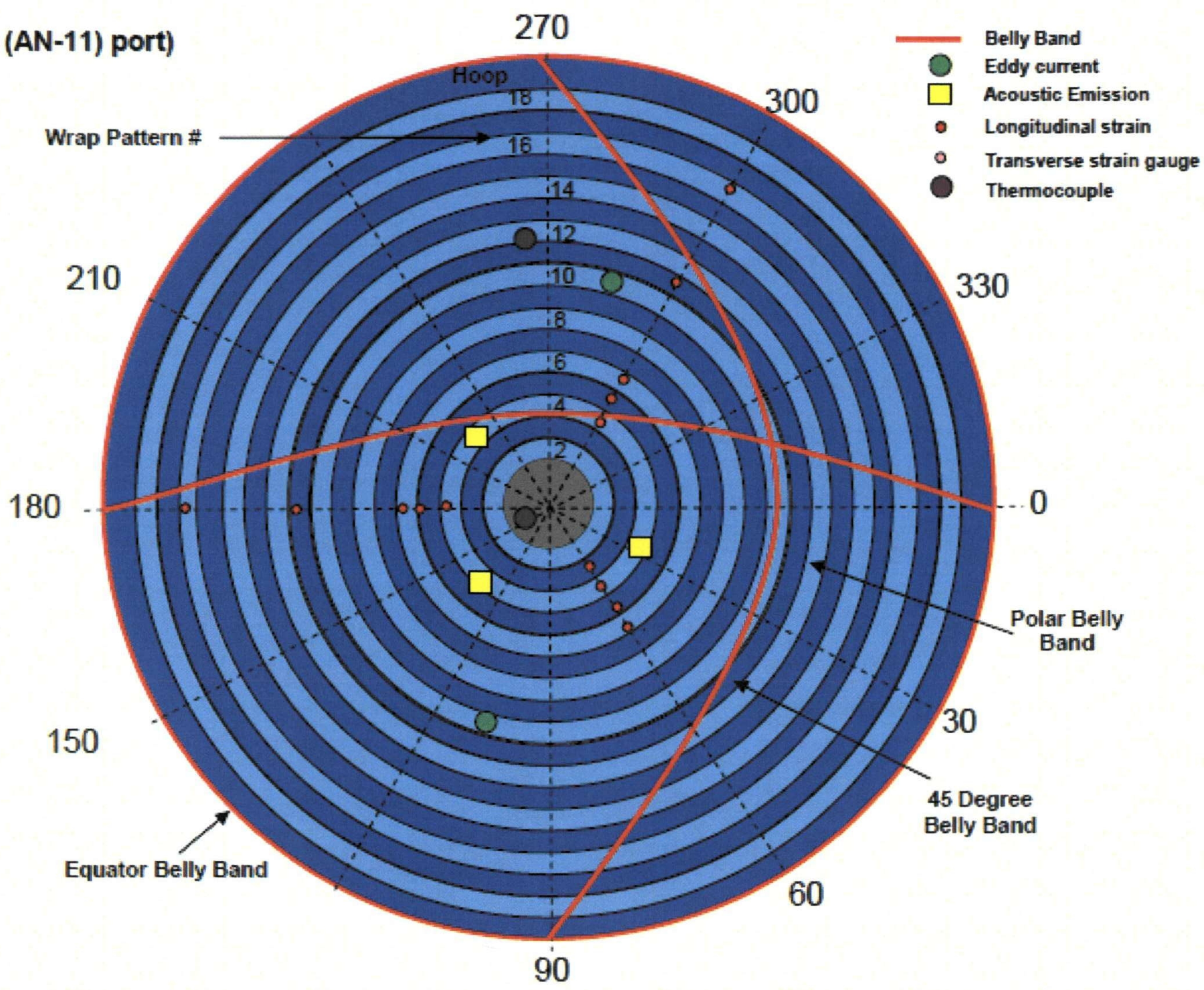
Test/Measurement	Purpose
Fluid Temperature	Test control parameter
Fluid Pressure	Test control parameter
Belly Bands	External diameter measurement
Acoustic Emission	Pinpoint failure location (triangulate)
Strain Gauges	Outer surface strain
Axial LVDT	Boss-to-boss growth
Eddy Current	Through wall thickness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

Instrumentation Map - Top

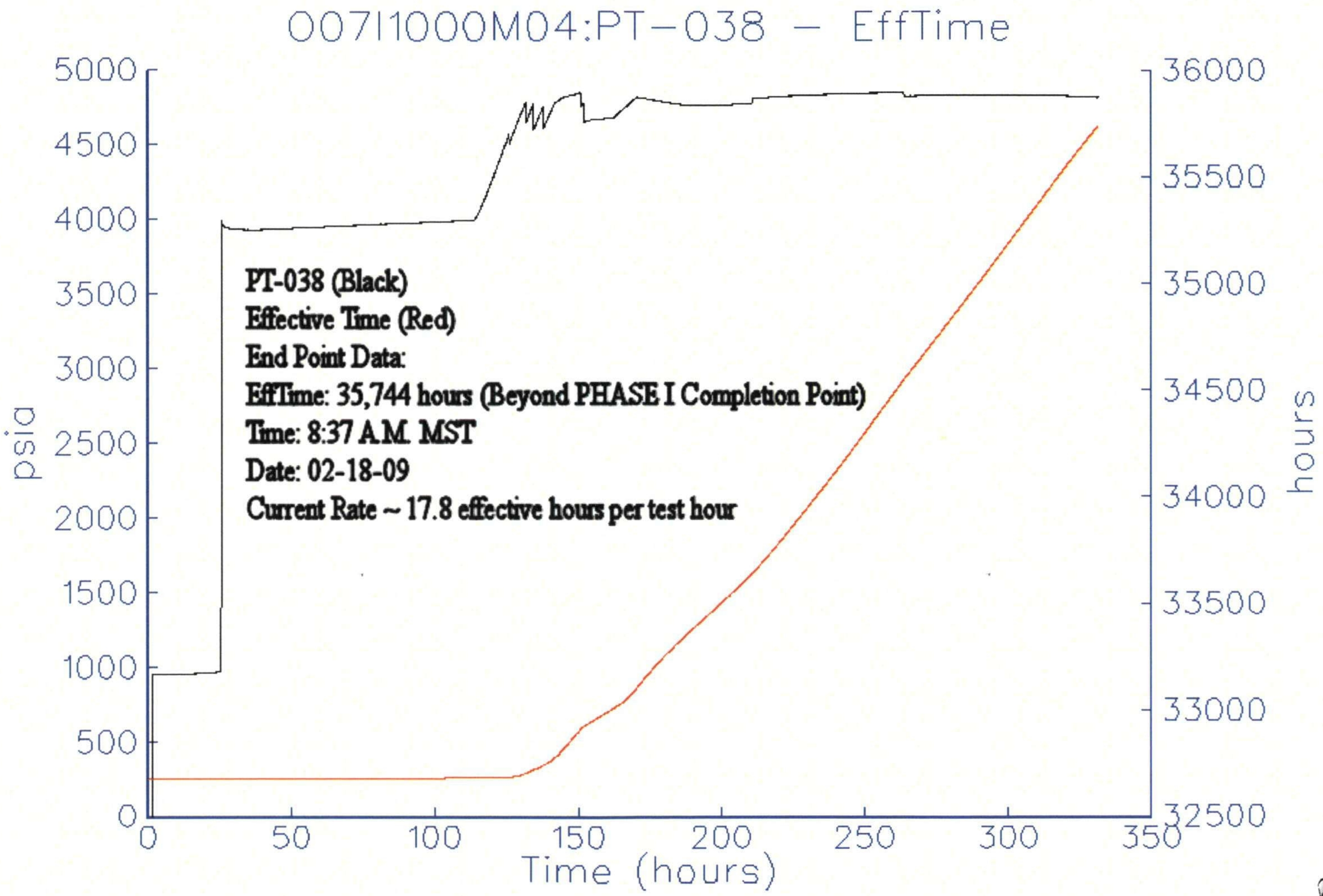


Instrumentation Map - Bottom

Bottom (AN-11) port)



Example of test results



Pressure and Effective Time

Test Results

- Phase 1 – 35,575 effective hours complete on 2/18/2009
  - Accumulated ~17 effective hours per test hour

- Phase 2 - 86,745 Effective hours estimated to be complete on ~3/27/2009
  - Accumulated ~75 effective hours per test hour

- Phase 3 – Tentative plans to increase pressure to approximately 5200 psi
  - Proof pressure is approximately 6400 psi
  - 5200 psi chosen based on previous near proof/burst test
  - Would accumulate ~300 effective hours per test hour
  - Phase 3 data would be both for potential shuttle life extension and to provide basis for testing of carbon wrapped vessels
    - Used by ISS and CxP

Space Shuttle Program