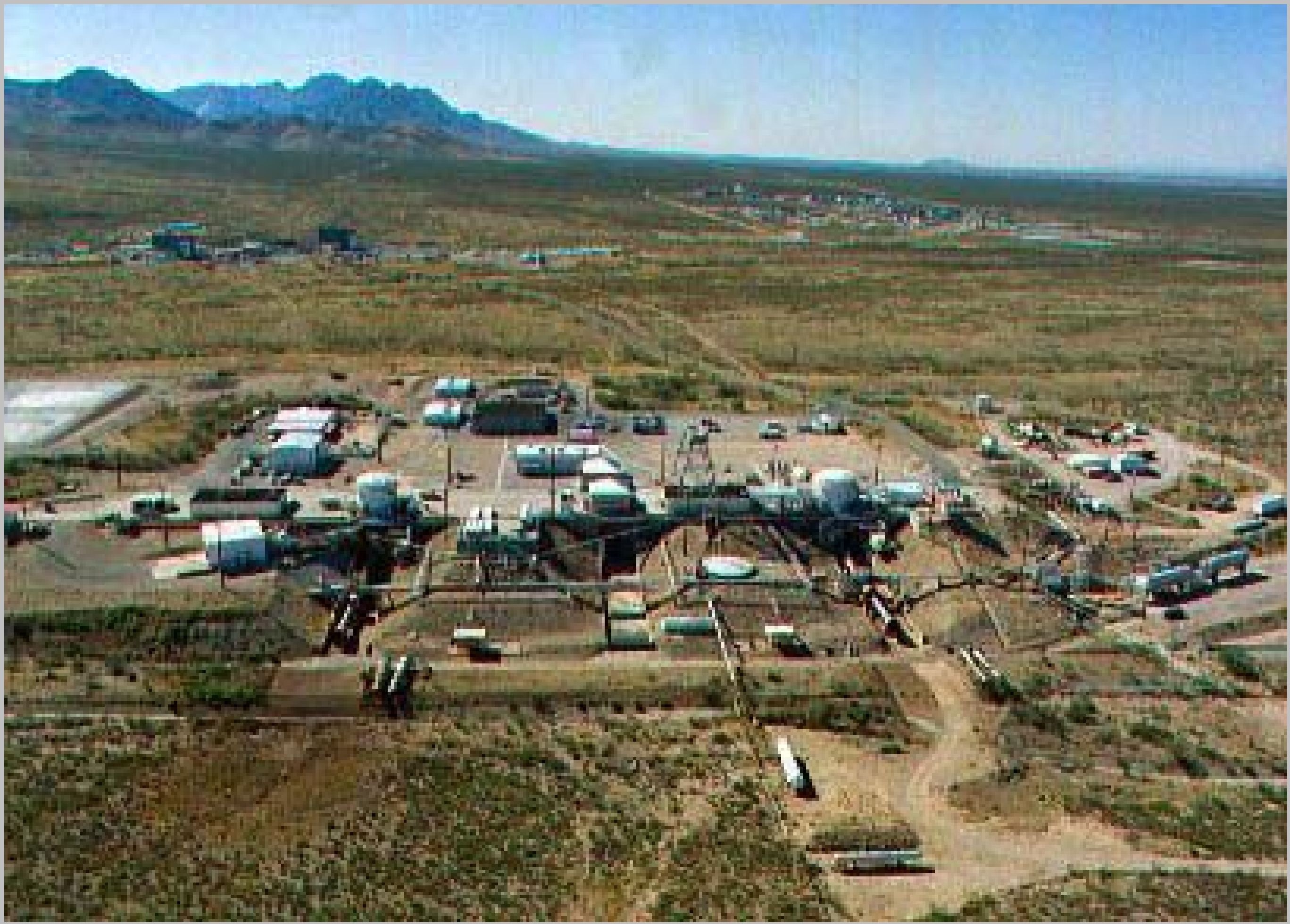
Hydrogen Initiative Symposium
The Purdue University Energy Center

Hydrogen and Storage Initiatives at the NASA JSC White Sands Test Facility

April 5, 2006

Stephen S. Woods
NASA WSTF Hydrogen Group

Aerial View Looking North



Introduction

- WSTF Hydrogen Initiatives
- WSTF Storage Initiatives
- Hydrogen Group Contact Information

Hydrogen Initiatives

- NASA WSTF Hydrogen Activities
  - Aerospace Test
  - System Certification & Verification
  - Component, System, & Facility Hazard Assessment
  - Safety Training
- Technical Transfer
  - Development of Voluntary Consensus Standards and Practices
  - Support of National Hydrogen Infrastructure Development

Hydrogen Initiatives

- Research and Development
  - Combustion Hazard Characterization
  - Component Development
  - Safety Research
    - Gaseous Leaks & Detection
    - Liquid Hydrogen Spills
    - Electrolyzer/Fuel Cell Test Bed

Storage Initiatives

Composite Overwrapped Pressure Vessels (COPV)

- Effects of Wear and Handling
- Effects of Aging

- Standards Development
- Inspection Training

Aerospace Test

- Delta Clipper
- Hydrogen Tank Boiloff tests

DC-X Executes Vertical Landing at WSMR

Static Firing of DC-X with 4 LOX/Hydrogen RL10-A5 Engines

System Certification & Verification

- Shuttle Flow Control Valve
- Shuttle LHRP
- PRSA

View of 6000 PSIA Tube Storage Bank for Flow Control Valve

Power Reactant Storage Assembly

Combustion Hazard Characterization

- Flammability & Ignition
- Fire, Deflagration, & Detonation
- Blast & Explosion

Explosion of 50 lb. LOX/LH2
at High Energy Blast Facility

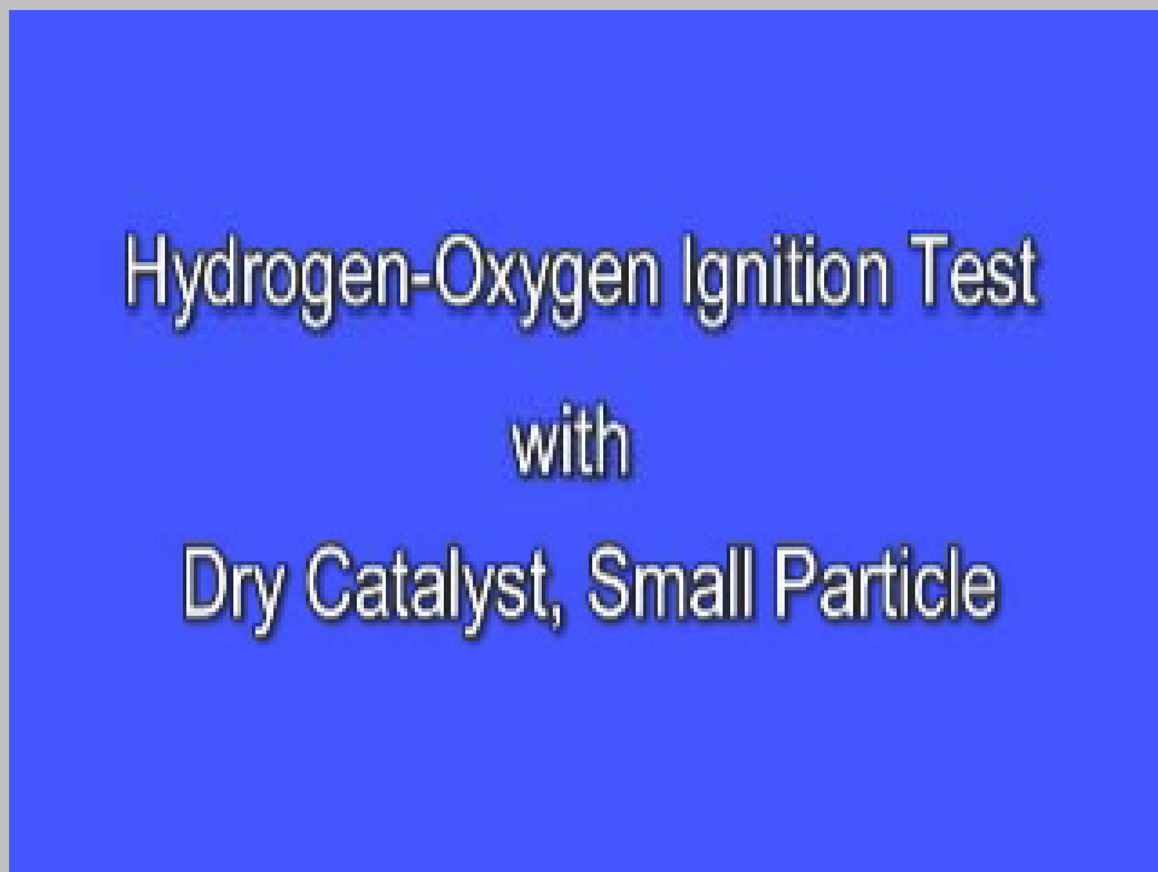
Tank Drop Test -- 75-ft-Dia Fireball
from Explosion of 2,200 lb. LOX/LH2

1500 Gal LH2 Spill, 3 MPH Wind

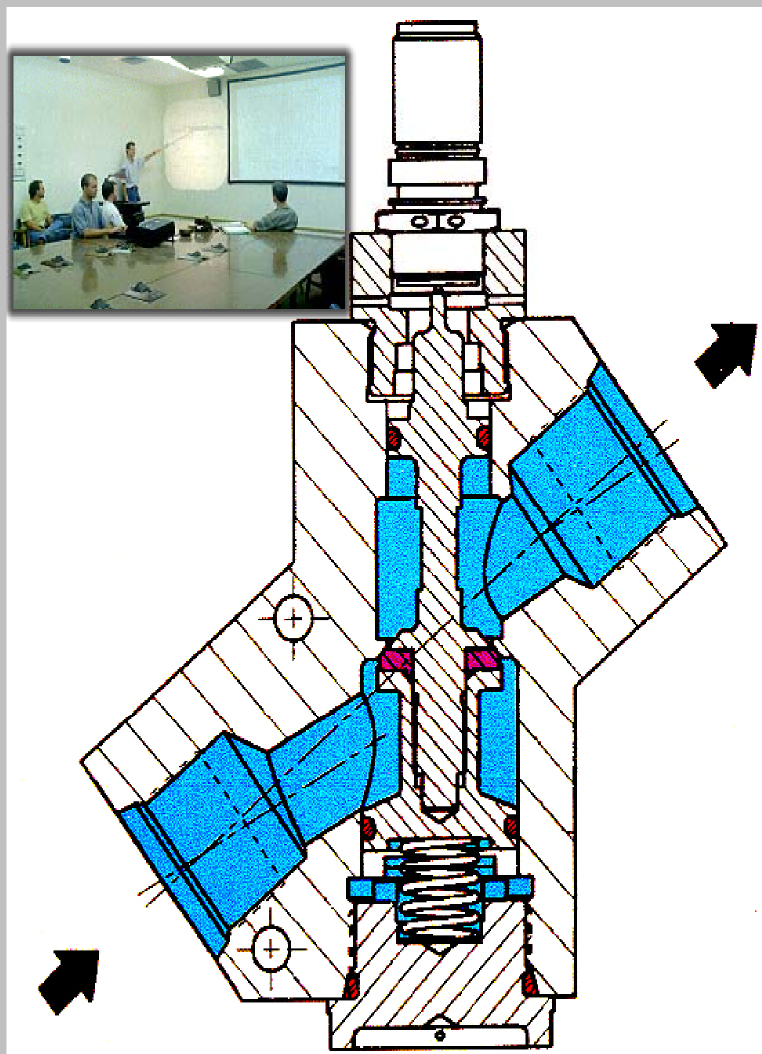
Combustion Hazard Characterization

- Combustion Hazard Handbooks
  - Fuel Hand Book
  - Combustion White Paper

Insert Image of H-O Vertical Det tube



Component, System, Facility Hazard Assessment



Safety Training

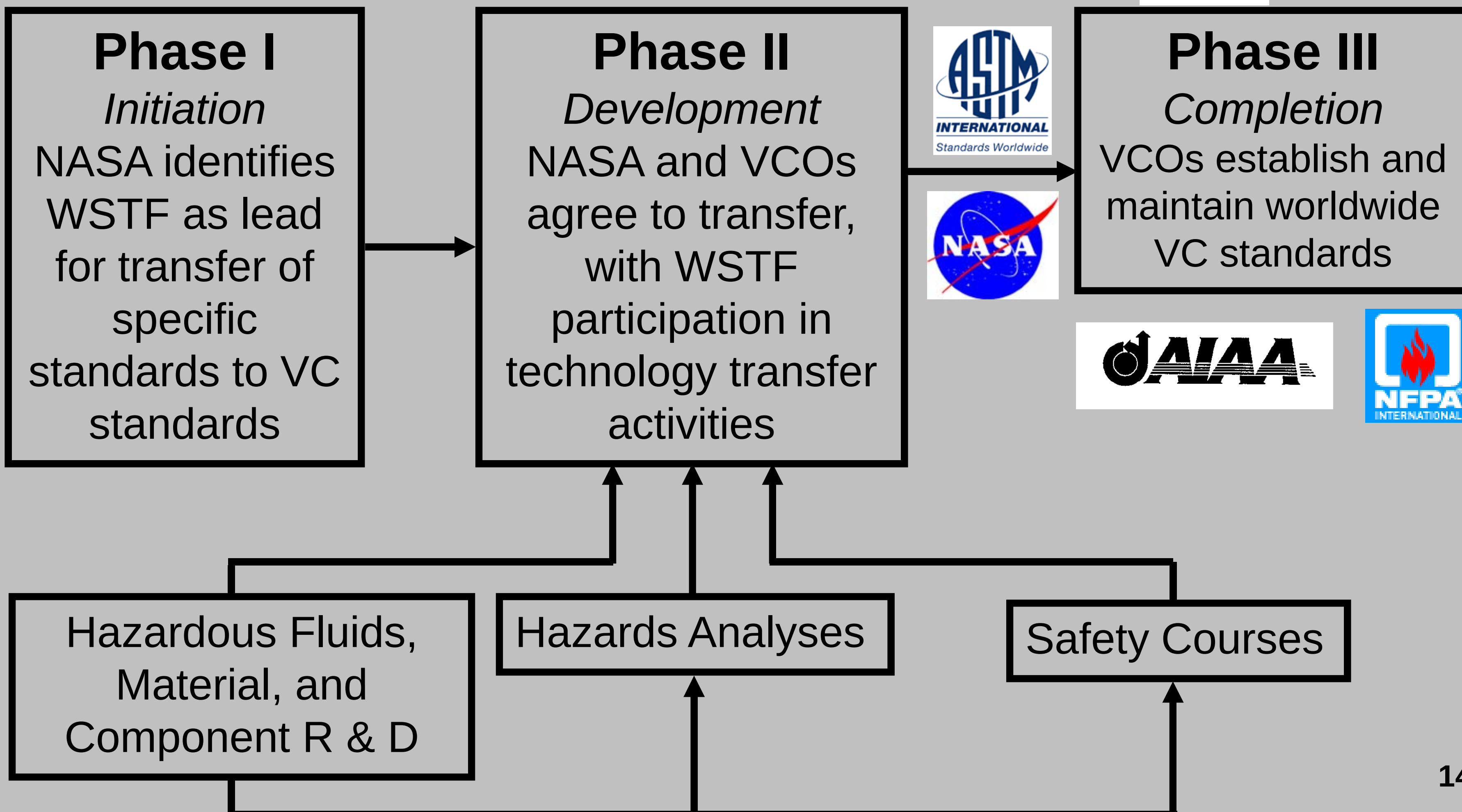
- Hydrogen Safety Course [14 hrs]
- Operators Course [4 hrs]

WSTF Support of the NASA Safety Training Center

Development of Voluntary Consensus Standards & Technology Transfer

- Aerospace Hydrogen Consensus Standards Managed with AIAA
  - AIAA/ANSI Guide to Safety of Hydrogen and Hydrogen Systems (G-095-2004)
- Support Review of ISO Commercial Standards for Hydrogen Systems
  - ISO/TC 197 Hydrogen Technologies
  - Member of US Technical Advisory Group to ANSI

Development of Voluntary Consensus Standards & Technology Transfer



Support of National Hydrogen Infrastructure Development

- DOE National Hydrogen Infrastructure Assessment – Sandia Labs Livermore
  - Unintended Releases
  - Materials Compatibility
- DOE Safety Panel
- Peer Review of Papers

1.4 kg GH2 at 5000 PSI in COPV

Bonfire Test with No Pressure Relief

Composite Overwrapped Pressure Vessels (COPV)

•COPVs are high-strength, light-weight containers for storing fuels and pressure media.

• COPVs use a thin metal or non-metal liner over-wrapped with a high modulus fiber and cured with an epoxy matrix.

Detrimental Effects to COPV Strength

- Mechanical Damage - cut or broken fibers on surface or sub-surface.
- Manufacturing Defect - misaligned damaged tow, buckled liner, etc.
- Stress Rupture - catastrophic failure due to long term sustained loading.

Standards Development

- AIAA S-081A: Space Systems - Composite Overwrapped Pressure Vessels (COPVs)
  - Working group member
- NGV-2: Compressed Natural/Hydrogen Gas Vehicle (NGV/HGV) Fuel Containers
  - Technical advisory group member

COPV Visual Inspection Training

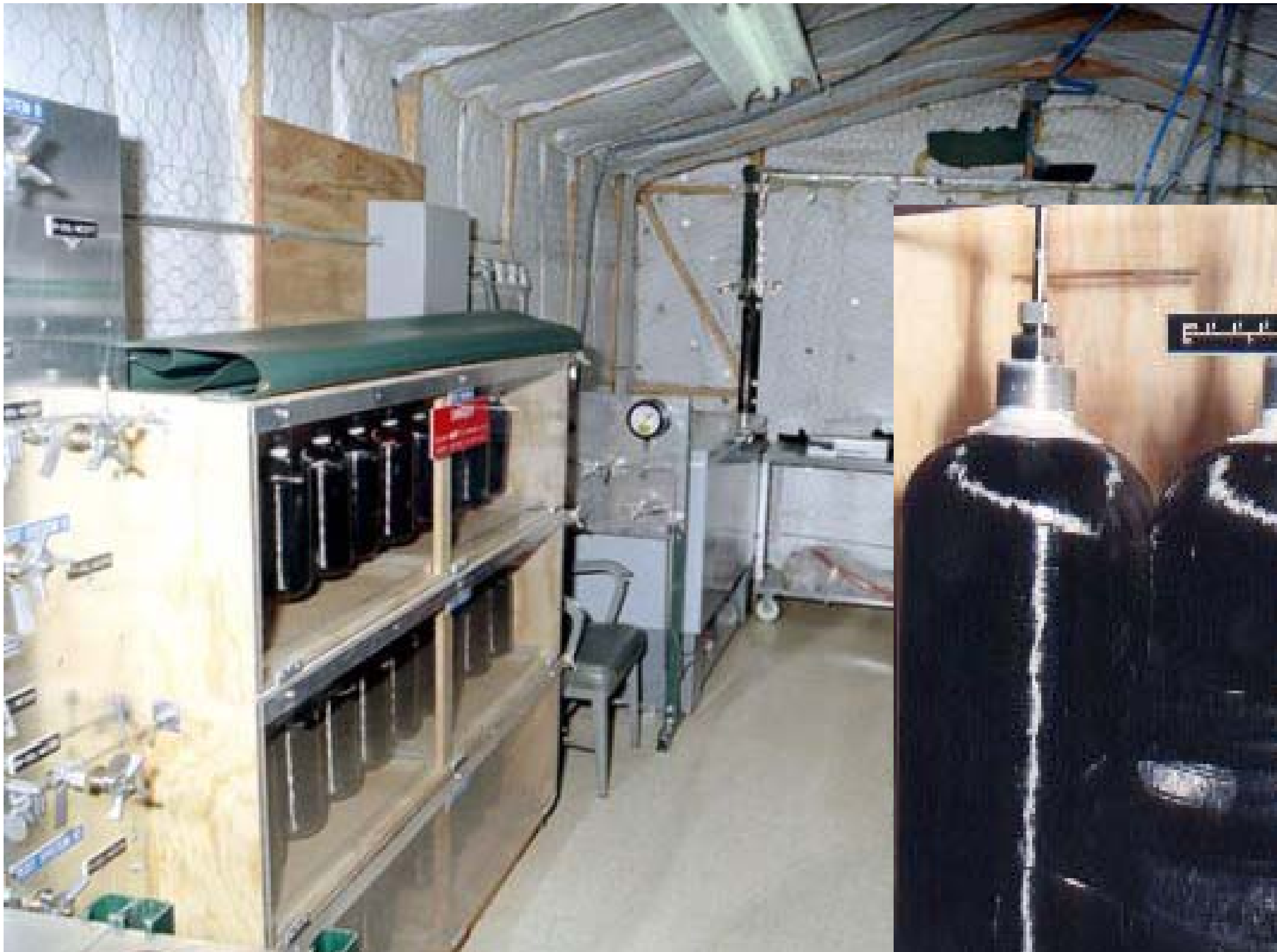
- Meets requirement in AIAA S-081A to have trained visual inspectors.
- Trains personnel to visually inspect the surface of composite pressure vessels (mainly carbon fiber) for indications of mechanical damage. The 2-day course also explains the importance of positively identifying mechanical damage by the use of secondary NDE techniques.

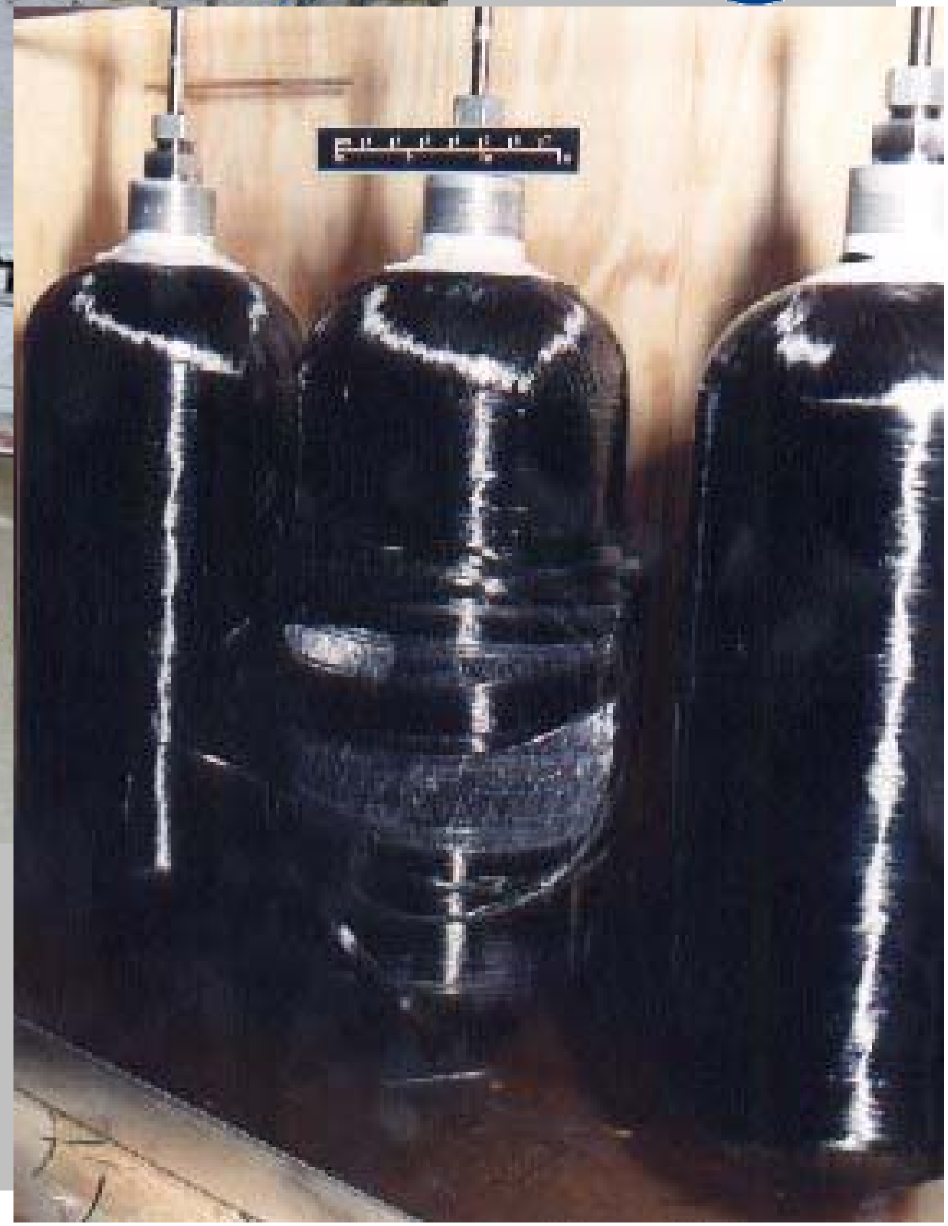
Cycle/Burst COPV

- Hydraulic Cycle Testing Up to 15K PSI
- Hydraulic Burst Testing of a Kevlar COPV
- High and Low Flow Rates at Various Volumes
- Axial Displacement, Strain Measurement (Conventional and Fiber Optic Bragg Grating), Load Measurement, Acoustic Emissions, Eddy Current, and Digital Image Correlation

Stress Rupture

- Long-term, High-stress Sustained Load Testing
- Numerous Fiber Systems on Experimental Test Bottles
- Dampened Pressure Systems Up to 6K PSI
- Ambient Temperature to -40 ^{o}F





COPV Analysis and Test Verification

- Integrated Composite and Structural Analysis (GENOA-PFA)
- Allows Complex Composite Ply Definition
- Filament Winding Routines for Overwrapped Vessels
  - Cylindrical
  - Spherical
- Verified Via Test and Evaluation (ASTM,WSTF, …)
- Combined Macro and Micromechanics Code

Numerical Analysis of Complex Composite Structures

- Nonlinear Static & Dynamic
- Creep
- Low and High Cycle Fatigue
- Impact Simulation
- Progressive Failure Analysis
  - Damage Tracking
  - Failure Mechanisms

Global and Local Analysis

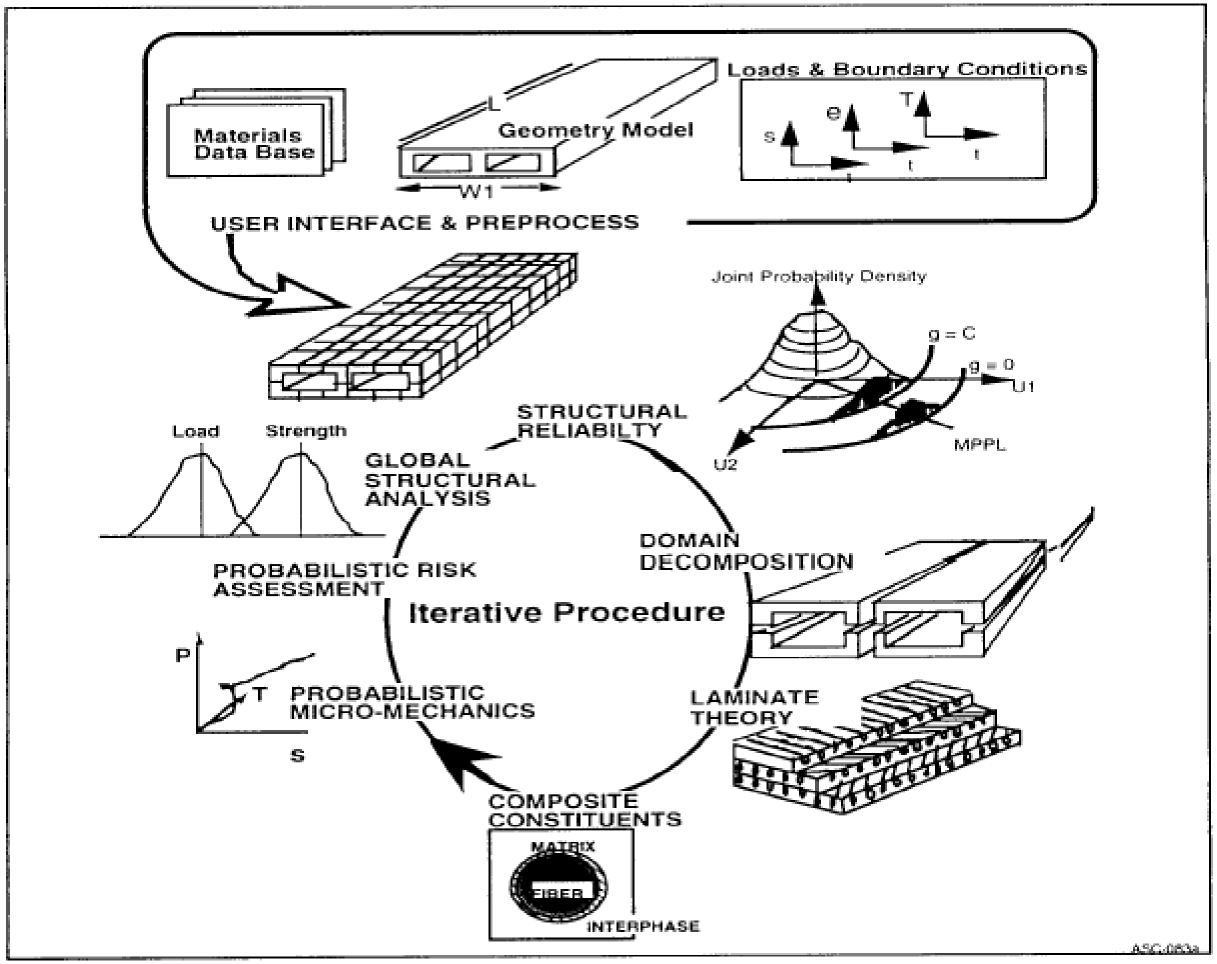
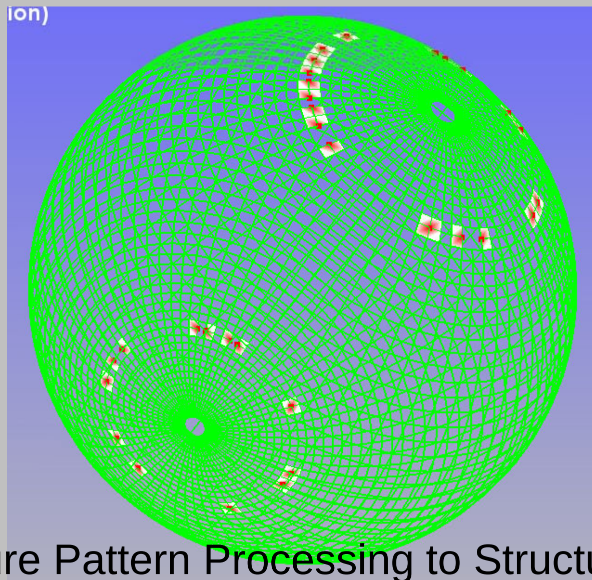
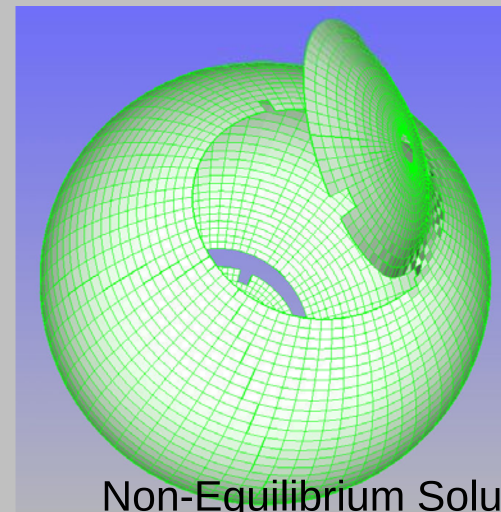


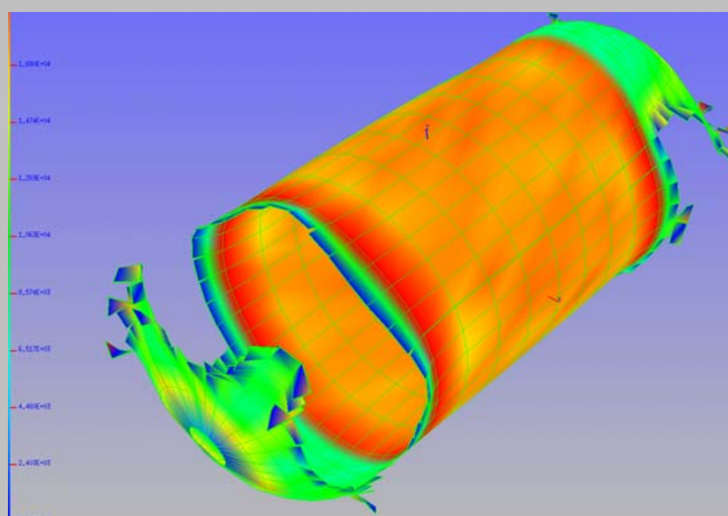
Figure 1.0.1-1. GENOA, Parallel Processing Software For Structural Analysis of Polymer Matrix Composite, Exploits Hierarchical Multi-Level on Macro and Micro Scales



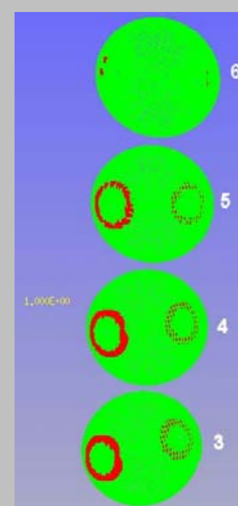
Fracture Pattern Processing to Structural Failure (Equilibrium Solution)



Non-Equilibrium Solution of Failure of Structure



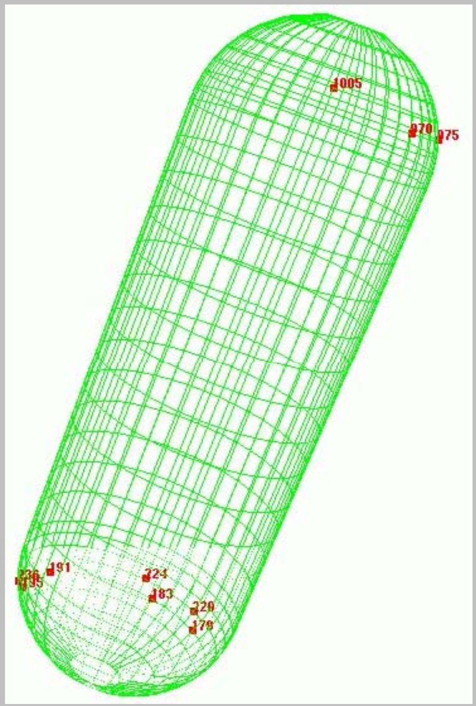
Stress at Cycle 212 (5980 psi)



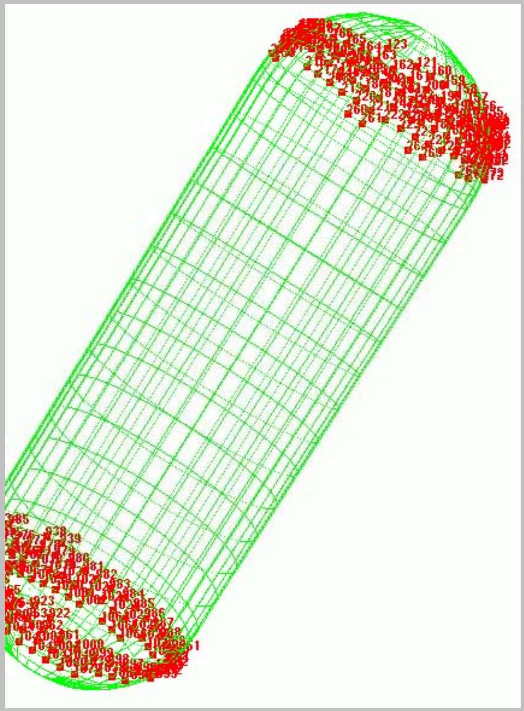
- Longitudinal Tensile Failure Pattern (Fiber Breaks)
- 7720 psi
- Model '11'
- Ply 3 next to liner
- Damage progression out towards surfaces

Damage Evolution: Final fracture at 61.5 Mpa (Design Burst Pressure = 62 Mpa) (AlphaSTAR)

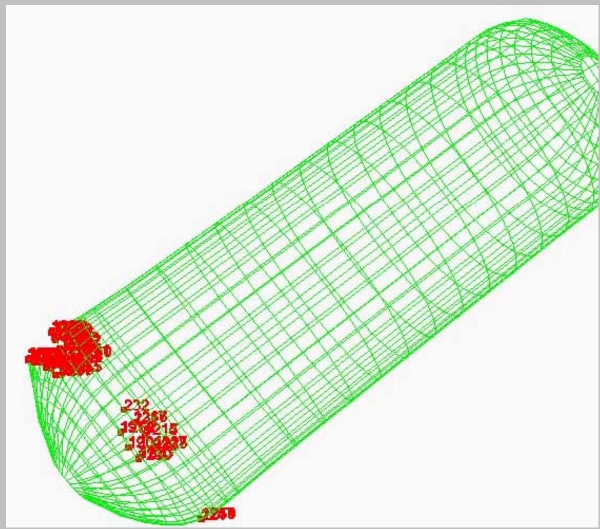
Failure Mechanisms



Damage Initiation



Damage Propagation



Final Fracture = 11,200 Psi

Facilities and Resources

- Expertise
  - Resource for Proper Hydrogen Practice
  - Systems Hazard Analysis
  - Hydrogen Safety Training
  - Standards Development
  - Multidisciplinary Force
- Facility Resources
  - Material Test
  - Cleanroom
  - Chemical Analysis
  - System & Component Testing (concrete test cells (800 area)
  - High Energy Blast Facility (<2000 lbs TNT eq. 700 area)
  - Liquid & Gaseous Hydrogen Supply (250 area)

Hydrogen Group Contact Information

NASA Program

- Harold Beeson [(505) 524-5542]
  - Miguel Maes [(505) 524-5677]
  - Nate Greene [(505) 525-7601]

Contractor Support

- Larry Starritt (Group Lead) [(505) 524-5676]
- Stephen Woods (Technical Lead) [(505) 524-5607]
- Max Leuenberger
- Stephen McDougle
- Rose Sepulveda
- Craig Robinson
- Chris Keddy