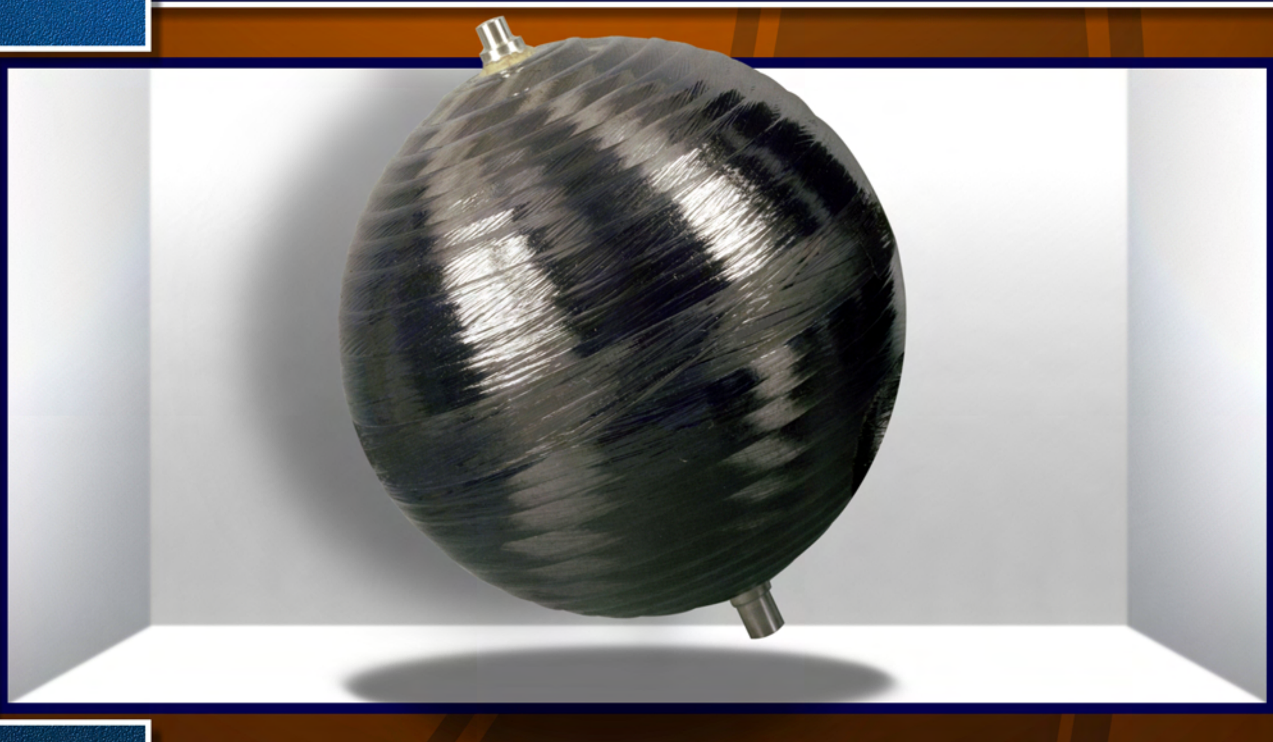
WSTF-RD-1198-001-13

Composite Conference

2012 Proceedings

Day 1



August 13-16, 2012, Las Cruces, NM

Points of Contact

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Composite Conference 2012

Agenda

Monday, August 13, 2012

All Day	Registration
	Tours - Spaceport (TBA)
	Exhibitor Set Up
Evening	Welcome Reception and Hors D'oeuvres

Tuesday, August 14, 2012

7:00 – 8:30 a.m.	Exhibit Set Up
8:00 – 8:30 a.m.	Registration and Continental Breakfast
8:30 – 9:00 a.m.	***Welcome to Composite Conference 2012***
	M. Huerta, PhD, DACC President
	H. Beeson, PhD, NASA Chair
	J. Jackson, PhD, Industry Chair
	A. Ruiz, DOE Chair
	J. Fekete, PhD, NIST Chair
9:00 a.m.	**Introduction of Speakers**
9:15 a.m.	***Keynote Speakers***
9: 15 – 9:30 a.m.	**Space Applications** (Fuel Storage, Life Support, Structure, Propulsion) *N. Greene, NASA/WSTF*
9:30 – 9:45 a.m.	**Vehicles** (Cars, Trucks, Busses, Forklifts, Loaders, Railroad Fuel Systems and Structure) *J. Keller, DOE*
10:00 a.m.	*Break*
10:15 a.m.	***Keynote Speakers (continued)***
10:15 – 10:30 a.m.	**Marine** (Ships and Barge Storage, Offshore Platform Storage) *D. McCloskey, NIST*
10:30 – 10:45 a.m.	**Pipelines and Repairs** *B. Smith, ORNL*
10:45 – 12:00 a.m.	Open time
12:00 – 1:00 p.m.	***Lunch (In Academic Resources Building)***

1:00 – 3:00 p.m.	**Session 1: Standards, Codes and Regulations** (Common Protocols) *J. Koehr, ASME Chair* *M. Toughiry, DOT Chair*
1:00 – 1:20 p.m.	**ASME Introduction to CPV standards activities** *G. Sheth, ASME*
1:20 – 1:40 p.m.	**Overview of ASTM Standards Activities Related to COPV** *J. Waller, NASA/WSTF*
1:40 – 2:00 p.m.	**Experience Developing ASME Section X Class III Pressure Vessels** *N. Newhouse, Lincoln Composites, Inc.*
2:00 – 2:20 p.m.	**NIST Overview of codes and standards activities** *D. McColskey, NIST*
2:20 – 2:40 p.m.	**Status of ESA Composite Pressure Vessel Codes and Standards** *G. Sinnema, ESA*
2:40-3:00 p.m.	**Break**
3:00 – 5:30 p.m.	**Session 2: Structures** (Progressive Failure and Structural Modeling) *P. Aggarwal, NASA/MSFC Chair* *G. Sinnema, ESA Chair*
3:20 – 3:40 p.m.	**Explicit Connections Between Elastic And Conductive Properties: Theory And Experimental Verification** *I. Sevostianov*
3:40 – 4:00 p.m.	**Elastic Plastic Fracture Analysis of an Aluminum COPV Liner** *S. Forth, B. Gregg, and N. Bailey*
4:00 – 4:20 p.m.	**Delamination Assessment Tool For Spacecraft Composite Structures** *G. Sinnema, P. Portela, P.P. Camanho, A. Turon, and M. Mendes Leal*
4:40 – 5:00 p.m.	**Break**
5:30 – 7:00 p.m.	Social Hour – Drinks and Appetizers - ***(In Academic Resources Building)***
7:30 – 10:00 p.m.	Open for Dinner Meetings and Events

Composite Conference 2012

Composites for Space Applications

Nathanael J. Greene
NASA White Sands Test Facility
Composite Core Capability Manager

Remarks

- Welcome to Composite Conference 2012
- Special thanks and welcome to participants in the NASA Composite Summit that started this collaboration.
- Special Thank You!
  - Joshua Jackson (MKF), Harold Beeson (NASA), James Fekte (NIST) and Antonio Ruiz (DOE) for chairing the conference
  - Session chairs and all NASA and NIST staff who worked hard to organize the conference with MKF
  - New Mexico State DACC's president Dr. Margie Huerta for hosting us in the East Mesa Facility
  - Angelique Lasseigne (G2M2) Crystal Lay (NMSU Mechanical and Aerospace Engineering) and Charles Nichols (NASA) for making STEM student sponsorship possible.

Why are we here?

- Need high strength materials in mass and cost constrained applications
  - Additional knowledge needed to use composites in our applications efficiently
  - Non-homogenus material
  - Anisotropic structure
  - Visceolastic response to loading
  - Multiple material interfaces
- Composite use in space systems requires
  - Advanced structural models
  - Life and failure mode prediction
  - Harmonized codes and standards
  - Materials and processes that address composite component variability
  - Reliable nondestructive evaluation

NASA's Use of Composites

Future Composite Space Vehicles (NASA's Composite Crew Module)

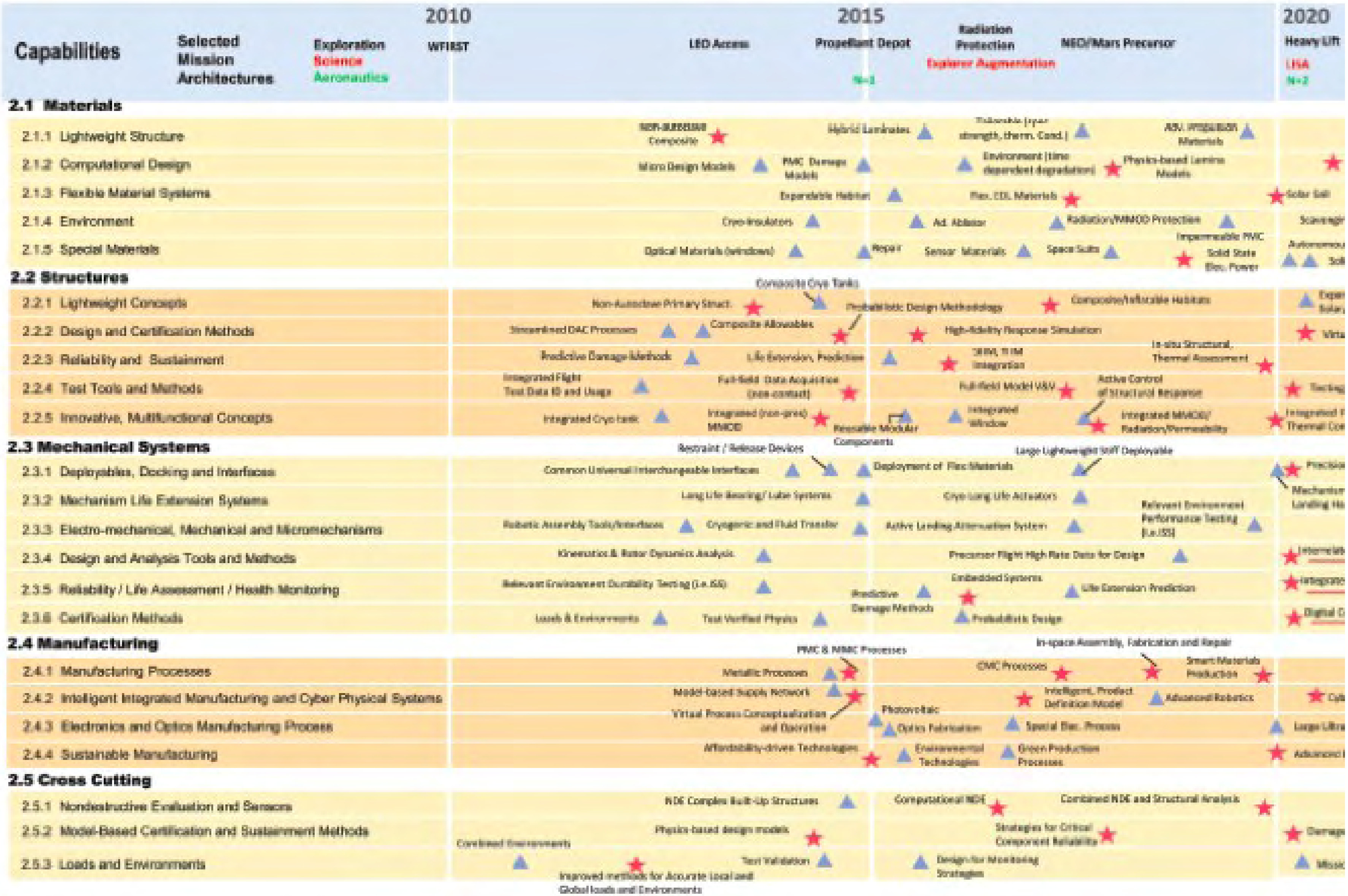
Growth in Composite use

Future	NASA Space Technology Roadmaps	Composite is Cross cutting technology, TA12, TA7
Today	NASA's COTS & CCDEV Vehicles	Composite Pressure Vessels Composite Structure
Today	Space Launch System	Composite Pressure Vessels Composite Structure
Today	Orion	Composite Pressure Vessels
1990s	International Space Station	Composite Pressure Vessels
1970s	Space Shuttle	Composite Pressure Vessels Composite Wing Leading Edge
1960s	Apollo	Pre-composites

Crosscutting for Space Technology Roadmaps

- Composites is a crosscutting technology for NASA's future missions
  - Low Earth Orbit Access and Propellant Depots (2015)
  - Mars Precursor Missions & Heavy Lift Vehicle (2020)
  - Advanced In-space Propulsion (2025)
  - Space Platforms (2030)
- http://www.nasa.gov/offices/oct/home/roadmaps/index.html

Composites Need: Space Technology Roadmap



Accelerated Growth in Composites

- Barriers to Growth
  - Funding
  - Cross disciplinary technological challenges
  - Maturity required to meet roadmap dates
- Steps to Accelerate Growth
  - U.S. intra-government collaboration
  - Government-industry partnerships
  - International communication and collaboration
  - Globally harmonized roadmaps for key technologies

NASA-Commercial Collaboration
Charlie Bolden (NASA) and
Elon Musk: (Space X)

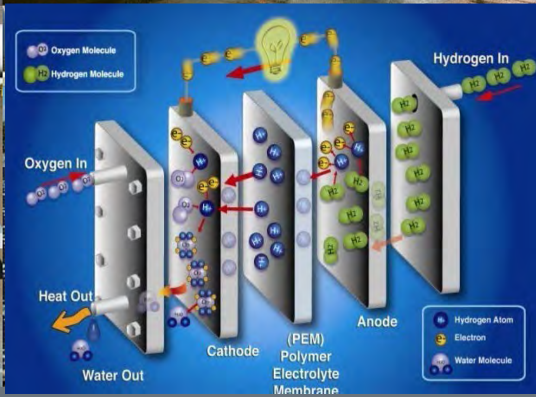
Let's Go!

- Address the global challenge of using composites in our applications by addressing common issues
- Excited to meet with leaders who are advancing composites in their applications
- Keep up with paradigm shift from metals to composites occurring in Aerospace, Automotive, Marine, and Pipelines

www.compositeconference.com

H2 Storage for Transportation Applications

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Composites Conference

Las Cruces, NM

August 14, 2012

Jay Keller, Ph.D
Consultant
U.S. Department of Energy
Fuel Cell Technologies Program

U.S. National Energy Strategy

"We've got to invest in a serious, sustained, all-of-the-above energy strategy that develops every resource available for the 21st century."

– President Barack Obama

"Advancing hydrogen and fuel cell technology is an important part of the Energy Department's efforts to support the President's all-of-the-above energy strategy, helping to diversify America's energy sector and reduce our dependence on foreign oil."

- Energy Secretary Steven Chu

"Fuel cells are an important part of our energy portfolio and these deployments in early markets are helping to drive innovations in fuel cell technologies across multiple applications."

- Dr. David Danielson
Assistant Secretary for Energy Efficiency and Renewable Energy

Demonstrations are essential for validating technologies in integrated systems.

Real-world Validation

Vehicles & Infrastructure

- >180 fuel cell vehicles and 25 hydrogen fueling stations
- 3.6 million miles traveled
- 152,000 kg of hydrogen produced or dispensed
- 2,500 hours (nearly 75K miles) durability
- 5 minute refueling time (4 kg of hydrogen)
- Vehicle Range: ~196 – 254 miles (430 miles on separate FCEV)

Buses (with DOT)

- H_2 fuel cell buses have a 42% to 139% better fuel economy when compared to diesel & CNG buses

Forklifts

- Over 130,742 total refuelings since 2009

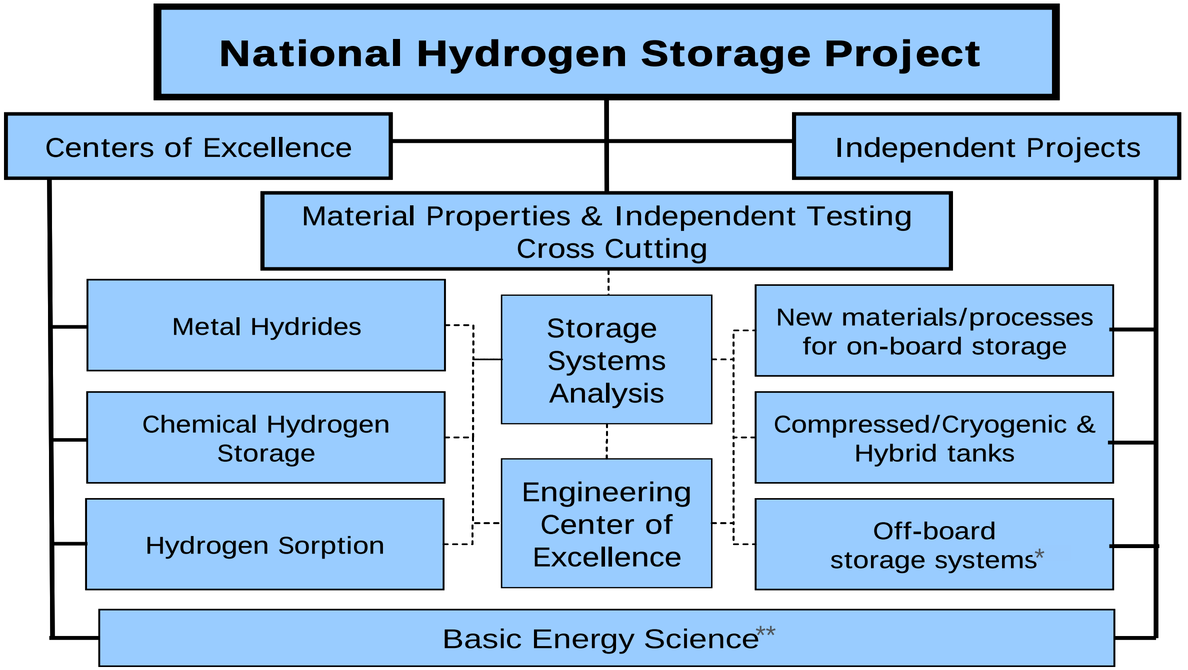
CHHP (Combined Heat, Hydrogen and Power)

- Demonstrated the world's first facility for co-producing hydrogen and power (with 54% efficiency)

The Program is developing technologies to enable high-capacity, low-cost storage of hydrogen.

KEY OBJECTIVE

> 300-mile driving range in all vehicle platforms, without compromising passenger/cargo space, performance, or cost



* Coordinated with Delivery R&D subprogram

**Conducted by the DOE Office of Science

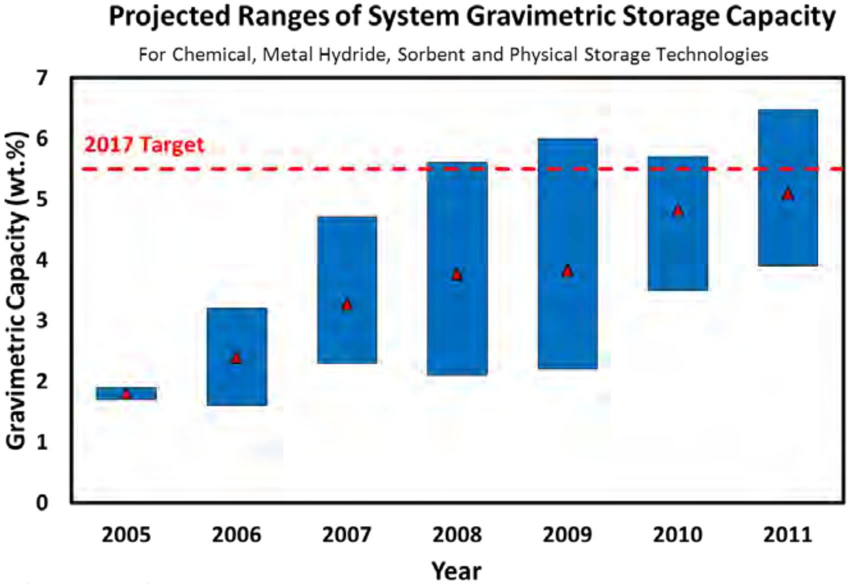
The National Hydrogen Storage Project involves the efforts of 45 universities, 15 federal labs, and 13 companies.

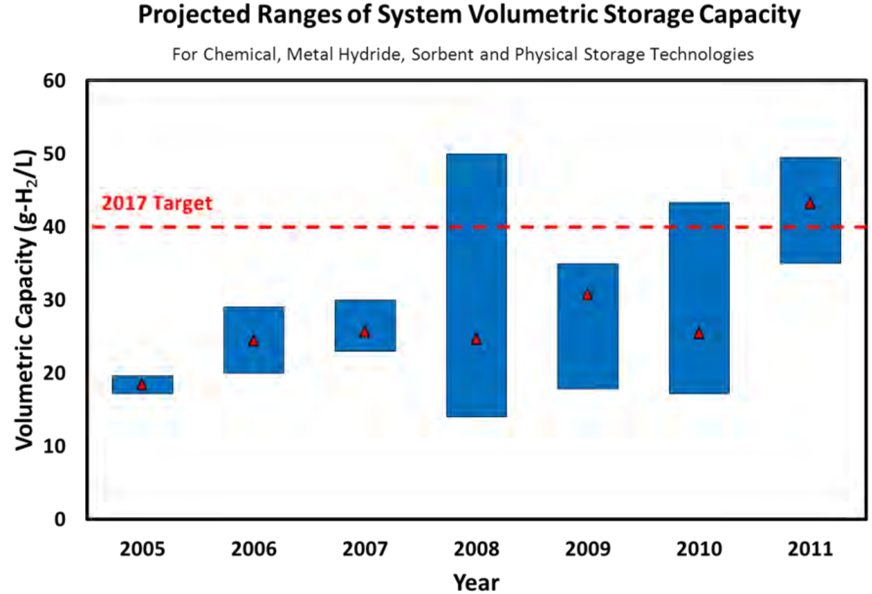
The Program has identified several promising new materials for high-capacity, low-pressure hydrogen storage—providing more than 50% improvement in capacity since 2004.

Hydrogen Storage R&D

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

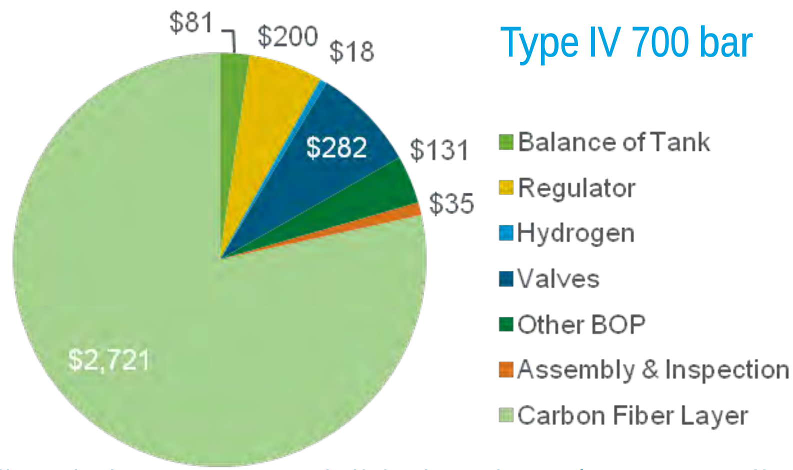
Projected Capacities for Complete 5.6-kg H_2 Storage Systems





- Validated a vehicle that can achieve 430 mile range (with 70 MPa Type IV tanks)
- Developed and evaluated more than 400 material approaches experimentally and millions computationally

Costs in the Carbon-Fiber Matrix



http://www.hydrogen.energy.gov/pdfs/review11/st002_law_2011_o.pdf

Status of the program

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Current Status	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Costs ($/kWh)
70 MPa compressed (Type IV)[a]	1.67	0.88	19
35 MPa compressed (Type IV)[a]	1.83	0.59	16
Cryo-compressed (27.6 MPa)[a]	1.90	1.44	12*
Metal Hydride ($NaAlH_4$)[b]	0.40	0.40	11*
Sorbent (MOF-5, 20 MPa)[b]	1.73	0.90	18*
Off-board regenerable (AB)[b]	1.39	1.27	NA

[a]: ANL/TIAX; [b]: HSECoE

*: Cost projections are from TIAX analyses of similar systems but not for the exact same design as the performance projections.

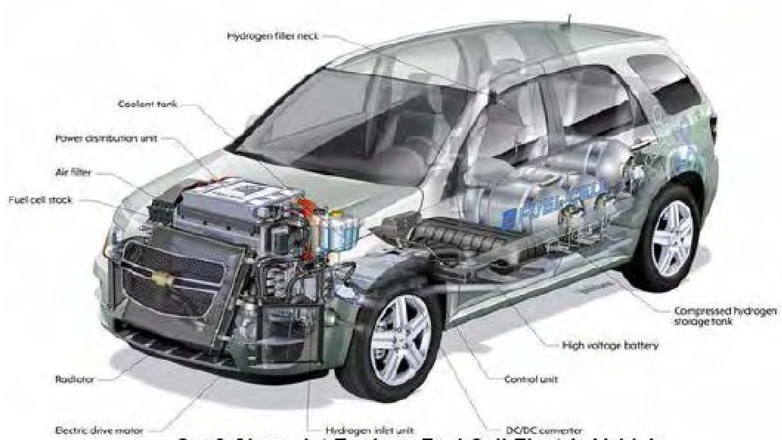
Status: Compressed Gas Storage

Compressed gas offers a near commercial solution; cost needs to be lowered.

Advantages
- Onboard refueling
- Available on near-term vehicles

Key Challenges
- Higher gravimetric & volumetric capacities
- Lowering overall costs

Forecourt Implications
- Precooling (70 MPa fast-fills) and compression are needed
- Thermal management during fill if precooling not utilized



Gen2 Chevrolet Equinox Fuel Cell Electric Vehicle

Status:
System capacity of 5.2 wt.% and 26 g-H_2/L for 70 MPa, 5.6-kg system

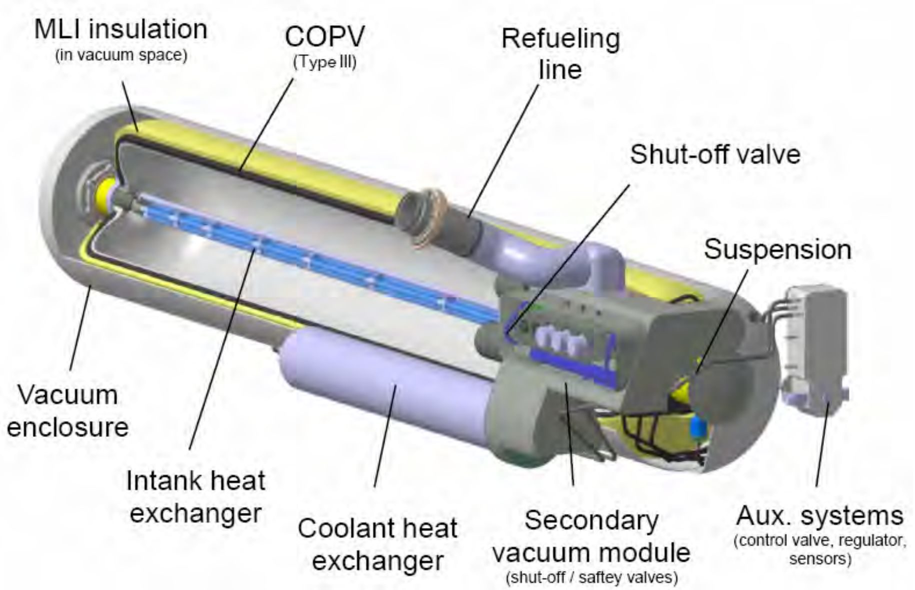
Research To Address Challenges:
- Carbon fiber cost reductions
- BOP improvements

Cryogenic pressure vessels have potential; needs include lower liquefaction costs and proven on-board systems.

Advantages
- Onboard refueling
- Higher capacity

Key Challenges
- Dormancy
- Effect of cryogenic conditions & cycling on tank materials

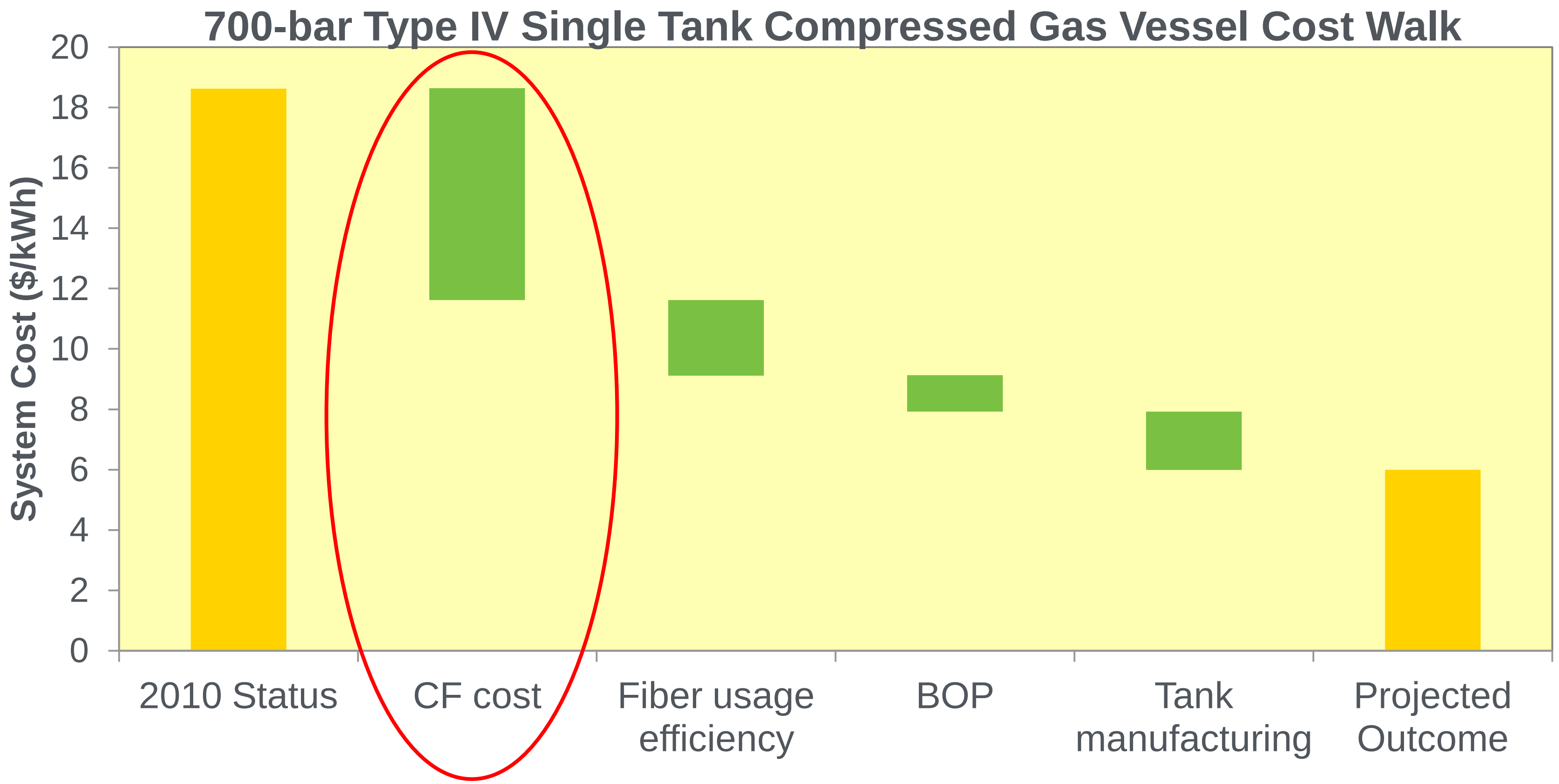
Forecourt Implications
- Need for energy & cost efficient liquefaction
- Possible compression for higher pressure fill



Status:
- System capacity of 5.7 wt.% and 43 g-H_2/L for 5.6-kg system

Research To Address Challenges:
- Effects on dormancy:
  - ✓ Driving and refill patterns
  - ✓ Ortho/para conversion
- Designs to minimize radiative losses

Compressed Gas Tank Cost Reduction Strategy



Carbon fiber contributes >75% of 35 and 70 MPa composite cylinder costs. Reductions through: Amount of fiber, cost of CF precursor & CF precursor processing.

Commercialization – roll out ~2015

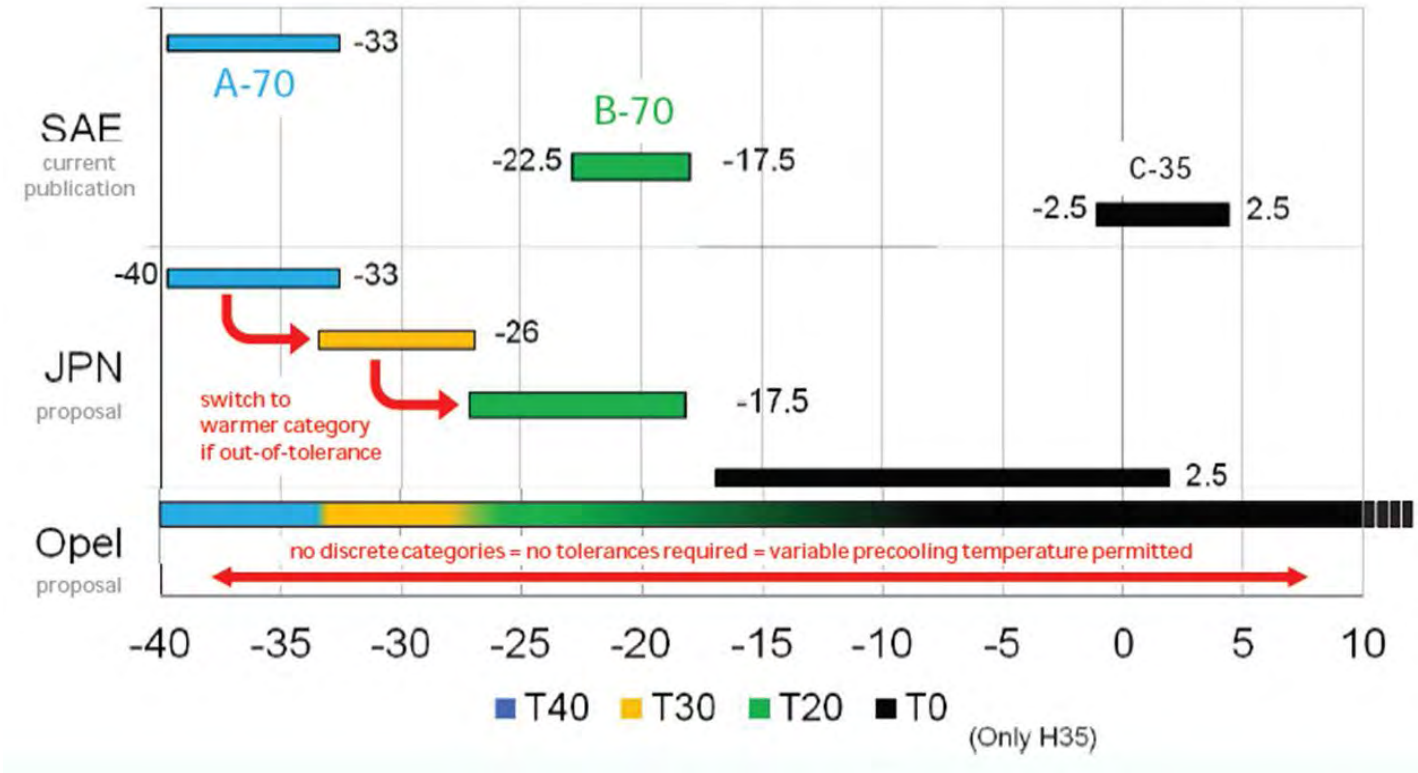
Commercialization will begin using compressed gas systems

- Allows some vehicle platforms to meet customer expectations
  - Cost remains a challenge
    - Carbon fiber contributes >75% of tank cost
    - Carbon fiber projects show potential to reduce carbon fiber costs by >30%
- Generation I – Infrastructure: 35 & 70 MPa, SAE J2601 compliant
  - 68 Stations in California
  - ~100 Stations in Germany
  - ~100 Stations in Japan
  - ~100+ Stations in Korea
  - New York and surrounding areas have a few and are planning for expansion

Next Steps

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

– Going forward, greater emphasis on:
  - o Engineering R&D, system analysis & model validation
  - o Compressed tank cost reduction
  - o Materials discovery R&D projects for 2015 & full-fleet targets



Acknowledgements

I wish to thank:

- My colleagues in the DOE Fuel Cell Technology Program;
- The conference organizers for the invitation
- And especially you for listening!

DOE Hydrogen Storage Team

Ned Stetson, Team Leader

Grace Ordaz
Jesse Adams
Katie Randolph
Scott McWhorter
Kathleen O'Malley

hydrogenandfuelcells.energy.gov

Presentation End

Program Mission

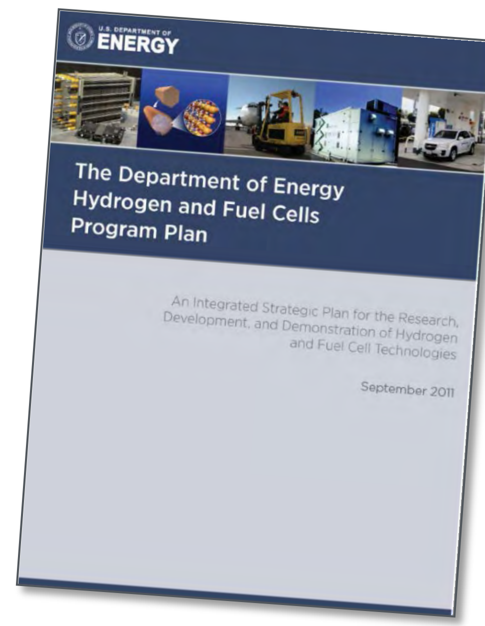
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

The mission of the Hydrogen and Fuel Cells Program is to enable the widespread commercialization of hydrogen and fuel cell technologies through:

- **basic** and **applied research**
- **technology development** and **demonstration**
- Addressing **institutional** and **market challenges**

Key Goals: Develop hydrogen and fuel cell technologies for:

1. **Early markets** *(e.g., portable power, ground support equipment and stationary power)*
2. **Mid-term markets** *(e.g., residential CHP, auxiliary power, buses and fleet vehicles)*
3. **Longer-term markets, 2015-2020** *(including mainstream transportation, with focus on passenger cars)*



An integrated strategic plan for the research, development, and demonstration activities of DOE's Hydrogen and Fuel Cells Program

http://hydrogen.energy.gov/roadmaps_vision.html

Fuel Cells: *Benefits & Market Potential*

The Role of Fuel Cells

Diverse Energy Sources & Fuels

- Biomass
- Natural Gas
- Propane
- Diesel
- Other Hydrocarbons
- Methane
- Methanol
- **Hydrogen** from renewables or low carbon resources

Clean, Efficient Energy Conversion

Fuel Cells

- Alkaline
- Direct Methanol
- Molten Carbonate
- Polymer Electrolyte Membrane (PEM)
- Phosphoric Acid
- Solid Oxide

Diverse Applications

Stationary Power

Transportation

Portable Power

Key Benefits

Very High Efficiency

- **> 60%** *(electrical)*
- **> 70%** *(electrical, hybrid fuel cell / turbine)*
- **> 80%** *(with CHP)*

Reduced CO_2 Emissions

- **35–50%+ reductions** *for CHP systems (>80% with biogas)*
- **55–90% reductions** *for light-duty vehicles*

Reduced Oil Use

- **>95% reduction** *for FCEVs (vs. today's gasoline ICEVs)*
- **>80% reduction** *for FCEVs (vs. advanced PHEVs)*

Reduced Air Pollution

- **up to 90% reduction in criteria pollutants** *for CHP systems*

Fuel Flexibility

- **Clean fuels** — *including biogas, methanol, H_2*
- **Hydrogen** — *can be produced cleanly using sunlight or biomass directly, or through electrolysis, using renewable electricity*
- **Conventional fuels** — *including natural gas, propane, diesel*

The Market Potential

By 2020, fuel cell and hydrogen markets could produce revenues of about $4.4 billion, including:

- **$4.0 billion from 5.3 GW of stationary power**
- **$255 million from 100,000 cars**
- **$144 million from 20,000 buses**

Independent analyses show global markets could mature over the next 10–20 years, producing revenues of:

- **$14 – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 – $97 billion/year for transportation**

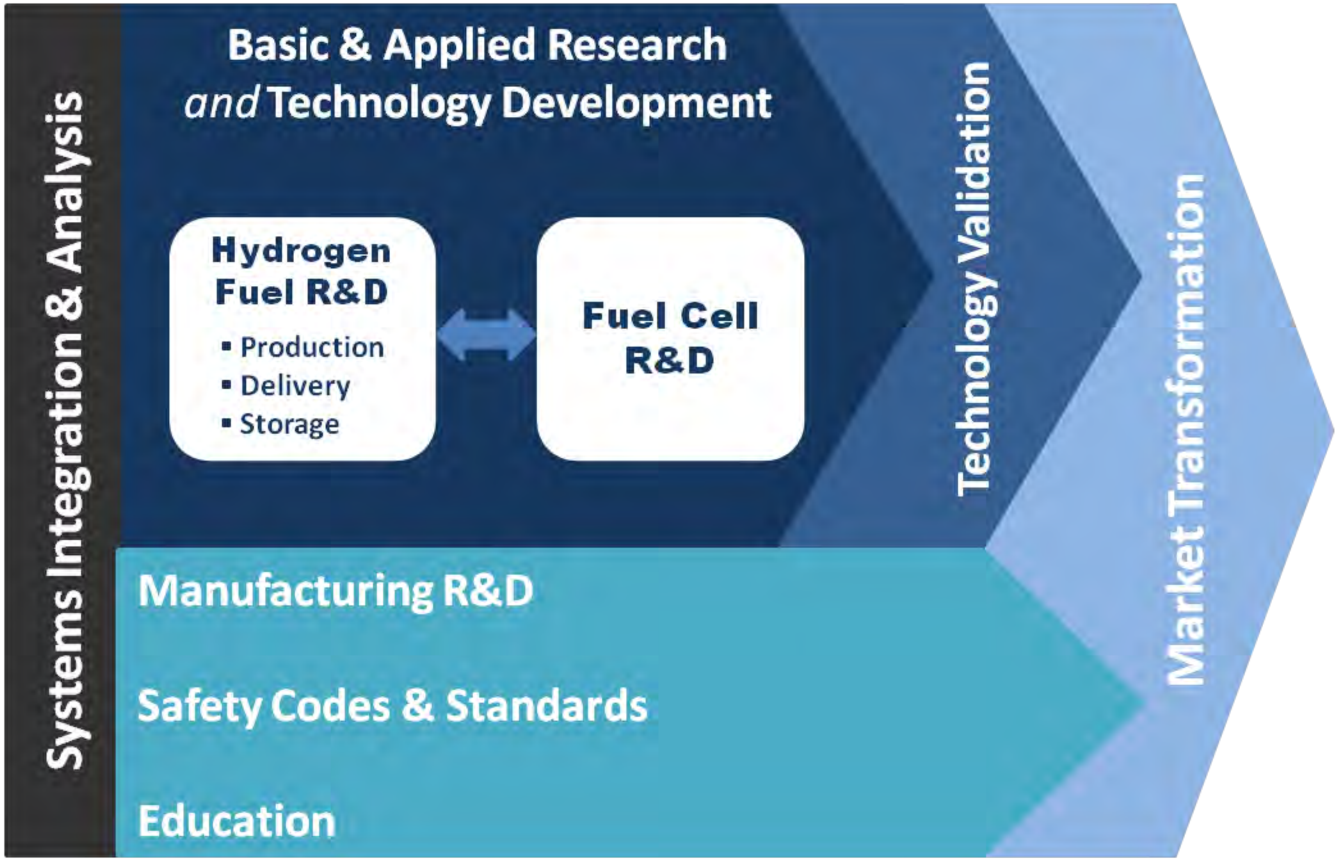
Independent analyses show widespread market penetration could create:

- **180,000 new jobs in the US by 2020**
- **675,000 jobs by 2035**;

Sources: LDV and bus projections are from Pike Research; 5.3 GW of stationary power assumes 10% of EIA's projected new installations through 2020; DOE Hydrogen and Fuel Cells Program Plan, www.hydrogenandfuelcells.energy.gov/pdfs/program_plan2010.pdf http://hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf

Current Program Structure

The Program is an integrated effort, structured to address all the key challenges and obstacles facing widespread commercialization.



WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power

The Program includes activities within the Offices of Energy Efficiency & Renewable Energy, Fossil Energy, Nuclear Energy, and Science.

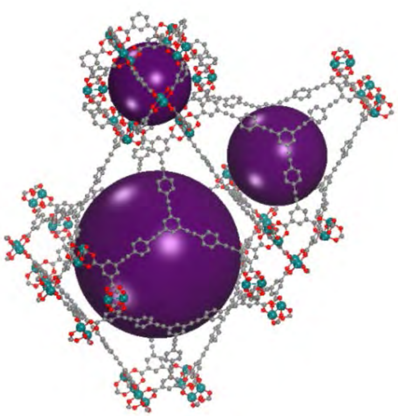
R&D to Close Gaps: Adsorbent Materials

Key Challenges

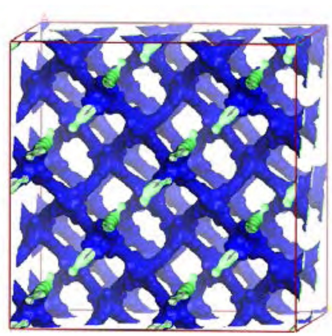
- Improving room temperature gravimetric & volumetric capacities
- Increasing desorption temperatures (towards ambient operation)

Research To Address Challenges

- MOFs: achieved 10 kJ/mol heat of adsorption on zwitteronic material
- MOFs & PPNs: Experimentally measured surface areas > 6000 m^2/g
- MOFs & PPNs: Measured excess capacities > 8.5 wt.% & > 28 g/L at 77K
- MOFs & PPNs: Shown to be air and water stable



NU-100
Cu-MOF

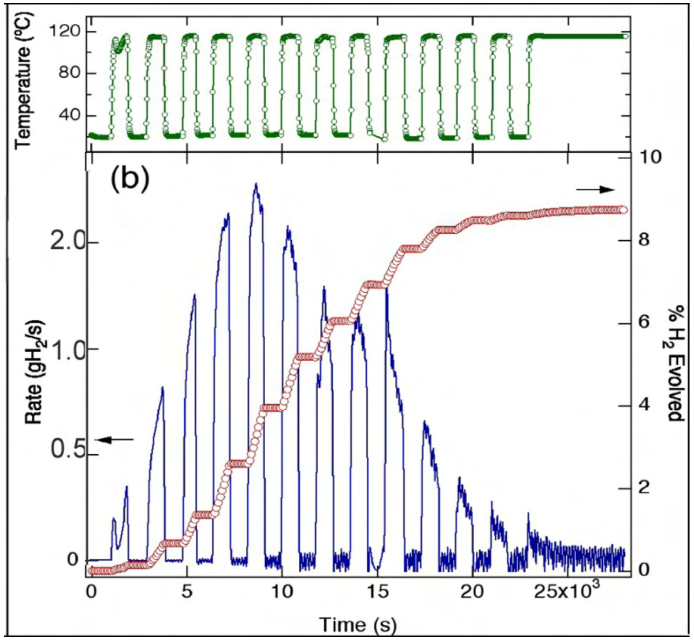


PPN-4(Si)

R&D to Close Gaps: Chemical Hydrogen Materials

Key Challenges → ***Research To Address Challenges***

- System complexity
- Fuel regeneration costs & efficiency
- Thermal control (exothermic release)
- Purity of hydrogen generated

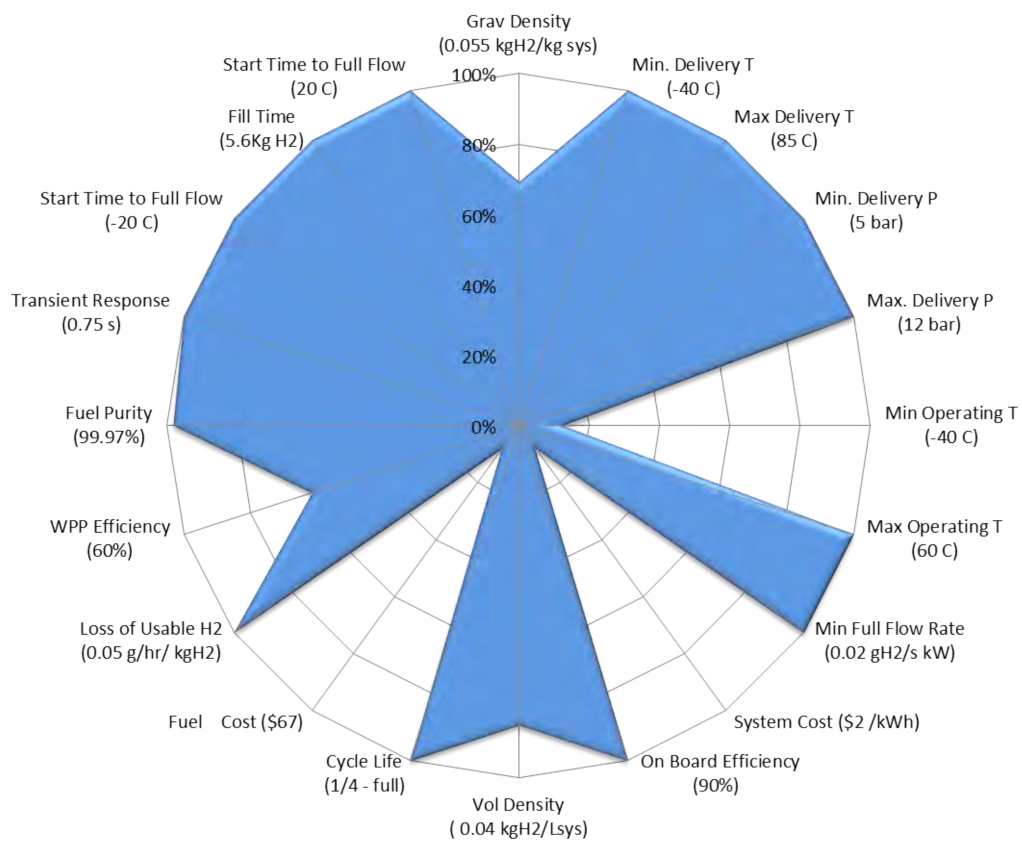


- AlH_3 slurry: 2X faster H_2 delivery than dry powder
- Micron-sized AlH_3 allows thermal control of H_2 release
- AB in ionic liquids: 10X increase in rate of H_2 release
- AB in ionic liquids: reduces impurity generation

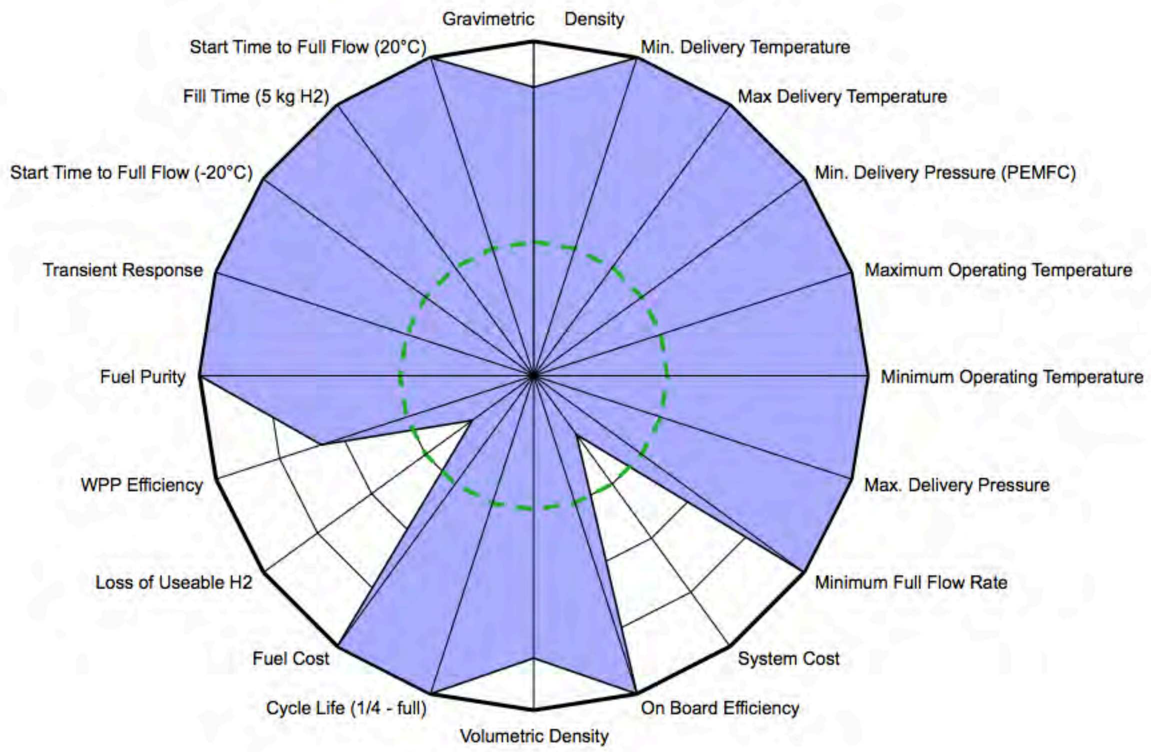
Key Issues & Challenges:

- Sufficient storage for driving range without impacting vehicle performance
- Kinetics
- Safety
- Capacities
- Impurities
- Heat management
- Efficiency
- Cost !
- Durability
- Engineering & manufacturing

CH (fluid Ammonia Borane) System Vs. 2017 Technical Targets



Representative Adsorbent System Status



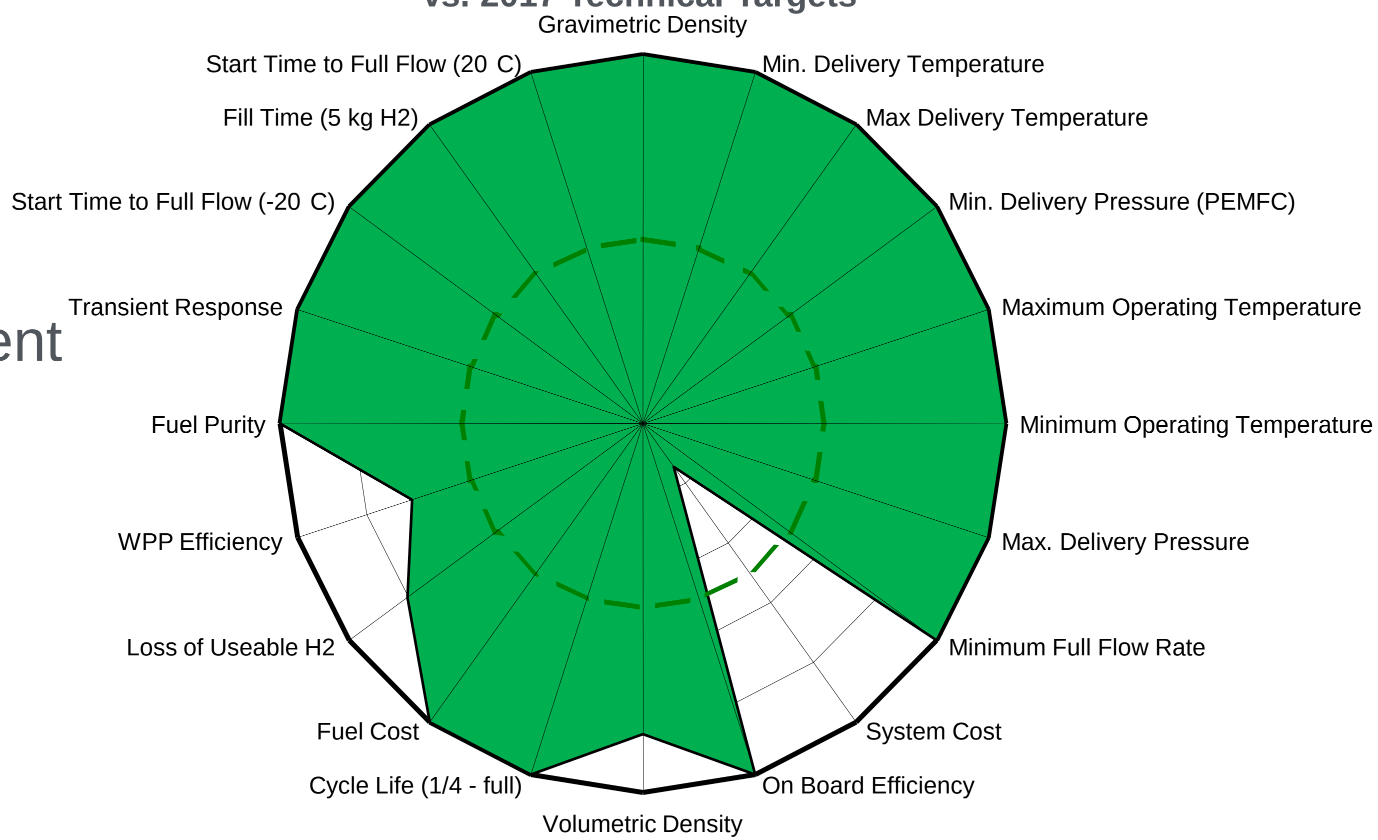
Activated Carbon Cryo-Adsorbent: Current Models vs. 2010 Targets

- **Advantages**: Onboard refueling; good fill/discharge kinetics; fueling heat rejection requirements moderate
- **Onboard issues**: system cost, dormancy and volumetric capacity are key issues
- **Station issues**: cryogenic operation (77K, -196°C), precooling
- **Status**: system capacity of 5.2 wt.% and 27 g-H_2/L

Key Issues & Challenges:

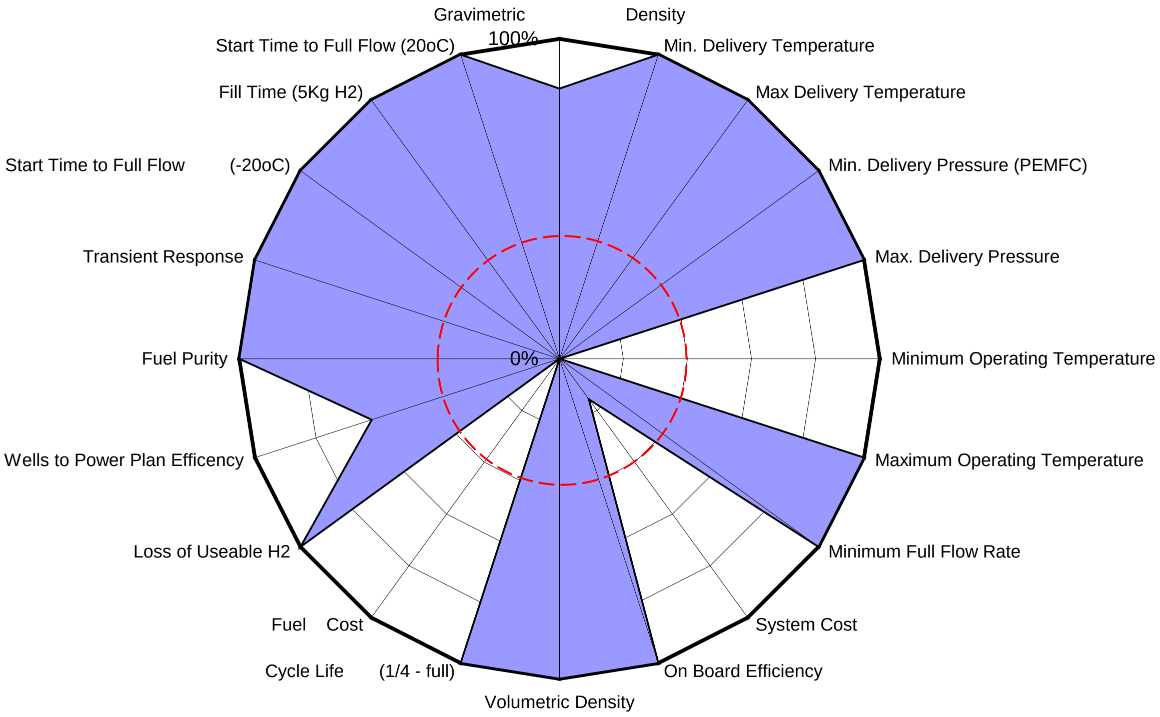
- Sufficient storage for driving range without impacting vehicle performance
- Kinetics
- Safety
- Capacities
- Impurities
- Heat management
- Efficiency
- Cost !
- Durability
- Engineering & manufacturing

Sorbent (MOF-5) System vs. 2017 Technical Targets



NOTE: For presentation, all metrics that exceed DOE targets are plotted at 100%

Representative Off-Board Generation System Status



Fluid Phase Ammonia Borane: Current Models vs. 2010 Targets

- **Advantages:** High capacity; high fuel delivery rate (to power plant); liquid or slurry formulations
- **Onboard issues**: system cost, fuel cost, minimum operating temperature
- **Station issues**: round trip efficiency, first fuel cost, and complexity of fueling infrastructure
- **Status**: system capacity of 4.2 wt.% and 38 g-H_2/L

Partnerships & Collaboration

Federal Agencies

- DOC
- DOD
- DOE
- DOT
- EPA
- GSA
- DOI
- DHS
- NASA
- NSF
- USDA
- USPS

– *Interagency coordination through staff-level Interagency Working Group (meets monthly)*

– *Assistant Secretary-level Interagency Task Force mandated by EPACT 2005.*

External Input

- Annual Merit Review & Peer Evaluation
- H2 & Fuel Cell Technical Advisory Committee
- National Academies, GAO, etc.

Industry Partnerships & Stakeholder Assn's.

- Tech Teams (USCAR, energy companies- U.S. DRIVE)
- Fuel Cell and Hydrogen Energy Association (FCHEA)
- Hydrogen Utility Group
- ~ 65 projects with 50 companies

Universities

~ 50 projects with 40 universities

DOE Hydrogen & Fuel Cells Program

State & Regional Partnerships

- California Fuel Cell Partnership
- California Stationary Fuel Cell Collaborative
- SC H_2 & Fuel Cell Alliance
- Upper Midwest Hydrogen Initiative
- Ohio Fuel Coalition
- Connecticut Center for Advanced Technology

International

- IEA Implementing agreements – 25 countries
- International Partnership for Hydrogen & Fuel Cells in the Economy – 17 countries & EC, 30 projects

National Laboratories

National Renewable Energy Laboratory P&D, S, FC, A, SC&S, TV, MN
Argonne A, FC, P&D, SC&S
Los Alamos S, FC, SC&S

Sandia P&D, S, SC&S
Pacific Northwest P&D, S, FC, SC&S, A
Oak Ridge P&D, S, FC, A, SC&S
Lawrence Berkeley FC, A

Lawrence Livermore P&D, S, SC&S
Savannah River S, P&D
Brookhaven S, FC
Idaho National Lab P&D

Other Federal Labs: Jet Propulsion Lab, National Institute of Standards & Technology, National Energy Technology Lab (NETL)

P&D = Production & Delivery; S = Storage; FC = Fuel Cells; A = Analysis; SC&S = Safety, Codes & Standards; TV = Technology Validation, MN = Manufacturing

Composite Conference 2012

Marine Applications

David McColskey
National Institute of Standards and Technology
Physical Scientist

Marine Transport of CNG

- Composite use in marine transport of compressed natural gas (CNG) is a developing (not new) industry
  - Simple system with relatively low initial investment cost
  - Demand for natural gas expected to increase to between 100 to 150 trillion cubic feet per day in the next 20 years
  - Approximately 60% of the worlds total natural gas reserves are in economically inaccessible (stranded) areas
  - Marine CNG is a viable solution to optimize these gas resources
- Marine CNG is an economical solution for medium transport distances when compared with LNG (longer distances)and pipelines (shorter distances)

Technology

- Compressing natural gas enables large amount of transport
- CNG is 1/3 the density of LNG and no expensive cryogenic liquefaction equipment is needed
- Gas can be compressed and stored in large composite overwrapped pressure vessels
- Ships pressure vessels can be fueled (compressed gas), transported to the intended destination, unloaded (decompression) and returned for refueling
- COPV technology is already in use in land vehicle transport

Certifications

- Composite reinforced pressure vessels have been certified and approved by ISO, ASME, Lloyd's Register and ABS….

- They are currently proposed for use in marine CNG transport applications.

Summary

- A number of designs, including coiled steel pipe as well as a variety of composite technologies are vying for a piece of the stranded gas reserves throughout the world.
- The lightweight, corrosion-resistant, highly reliable, cost-effective composite systems appear to be very promising.

Thank you

Composite Conference 2012

Composite Pipelines for Hydrogen Delivery: Knowledge Gaps in Performance, Durability and Safety

Barton Smith, Barbara Frame, and Lawrence Anovitz
Oak Ridge National Laboratory

August 14, 2012

DOE Fuel Cell Technology Program–H_2 Delivery

- Delivery Program Goal: Develop and promote H_2 delivery technologies that enable market introduction and long-term viability of H_2 as an energy carrier for transportation and stationary power
  - H_2 production at dispensing station eliminates transportation costs, but production costs are higher than centralized production because economies of scale are sacrificed
  - Delivery costs associated with truck transportation of compressed and cryogenic H_2 are significant

DOE Fuel Cell Technology Program–H_2 Delivery

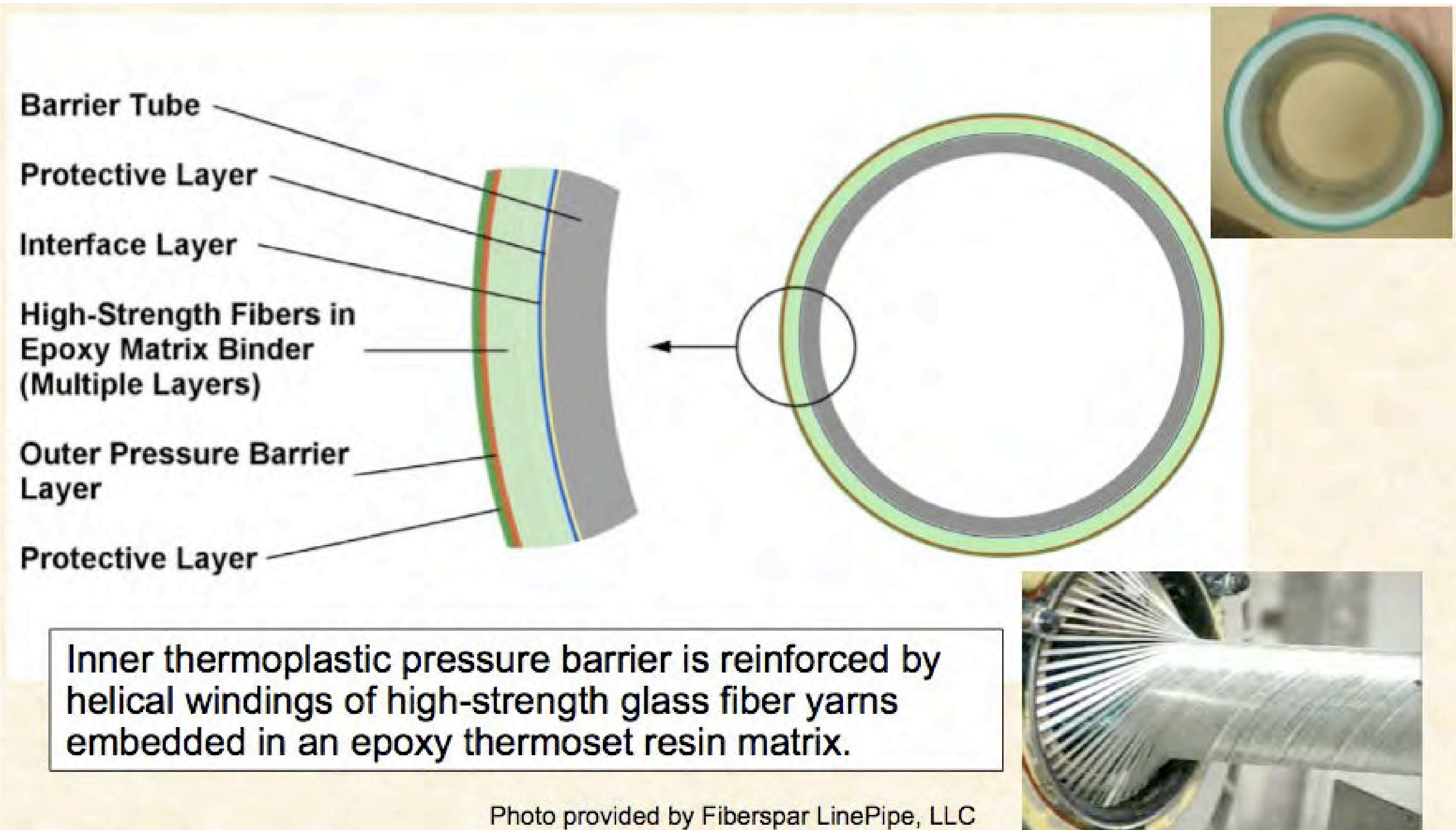
- Pipeline delivery of hydrogen is regarded as a *long-term* delivery solution
- Existing hydrogen pipeline infrastructure in U.S. was built using low-alloy, high-strength steels
  - These steels can lose ductility via H_2 embrittlement
  - Capital costs for installation of steel pipeline are too high to provide cost-effective H_2 delivery
    - Delivery cost target (all delivery modes): < \$2.00 per gallon gasoline equivalent (1 gge ~ 1 kg H_2)
  - H_2 compatibility of steel pipelines might be manageable, but installation cost reductions are unlikely

FRP Composite Pipelines are Viable Low-cost, High-Performance Alternatives to Steel Pipelines

- Fiber-reinforced polymer (FRP) pipelines are viable alternatives to steel pipelines and have the potential to meet FCT Program technical targets for capital installation costs and safety
- FRP pipelines and constituent materials tested to-date have been demonstrated to be intrinsically compatible with high-pressure hydrogen
- FRP pipelines are commercially available from many manufacturers

FRP gathering lines being entrenched for upstream oil and gas operations. Photo provided by Fiberspar, LLC.

Representative FRP Pipeline Architecture and Construction



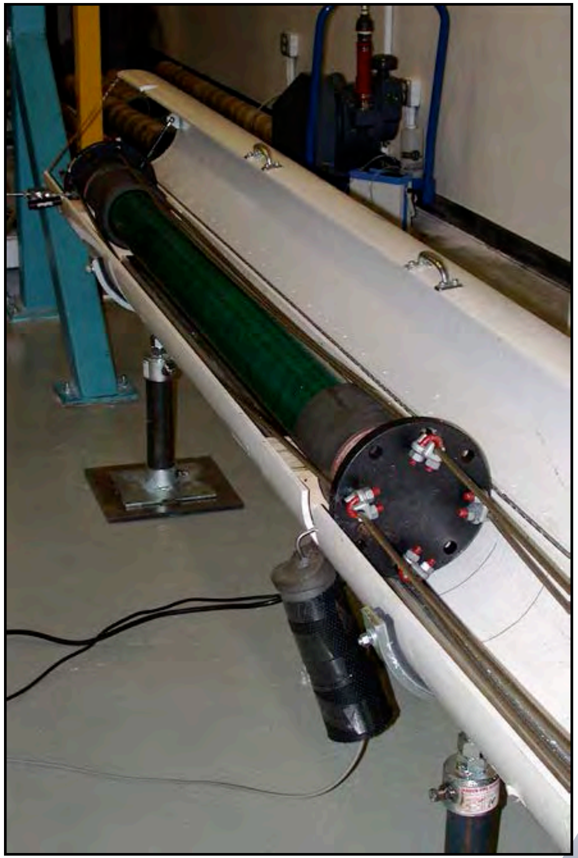
FRP Pipelines can Achieve Capital Cost Technical Targets

Estimate for capital investment, based on current pricing for FRP pipelines, indicates FRP pipeline could meet 2020 cost target for transmission pipeline installation

Gaseous Hydrogen Delivery			
Transmission Pipeline			
	2009 Estimate for Natural Gas Pipeline	**2012 Estimate for FRP Pipeline**	**2020 FCT Target**
Total capital investment, in $/mile for 8-inch equivalent pipeline (excluding costs for ROW and permitting)	**765,000**	**570,000**	**710,000**
H_2 leakage, in kg H_2/mile/y		**<60 (<0.1%)**	**<780 (<0.5%)**

FRP Pipelines Perform Well with Respect to H_2 Leak Rates

- We measured H_2 permeation and leakage rates in pipelines with different architectures and materials, at room temperature and max operating temperature (~60°C)
- Measured leakage is much lower than predicted and is significantly below the leakage target of 0.1%



Pipeline leak rate measurement apparatus in ORNL Polymer Matrix Composites Assembly Laboratory

H_2 Leakage in FRP Pipelines is Significantly Less than Leakage Target

⇒ Using measured leak rates in two FRP pipelines (different liner materials and reinforcement architectures), we estimated H_2 loss due to leakage would be significantly less than that present in natural gas pipeline infrastructure

Specimen	Construction	Test Pressure (bar)	Measured Leak Rate (mol/h/m)	Predicted Leak Rate (mol/h/m)
Fiberspar LinePipe™ 10-cm ID	0.5-cm thick PE-3408 liner, glass fiber epoxy matrix reinforcement	100	3×10^{-4}	9×10^{-3}
Polyflow ThermoFlex® 4.8-cm ID	0.34-cm thick PPS+PA liner, aramid braid reinforced, PP jacket	100	5×10^{-4}	$\sim1\times10^{-3}$

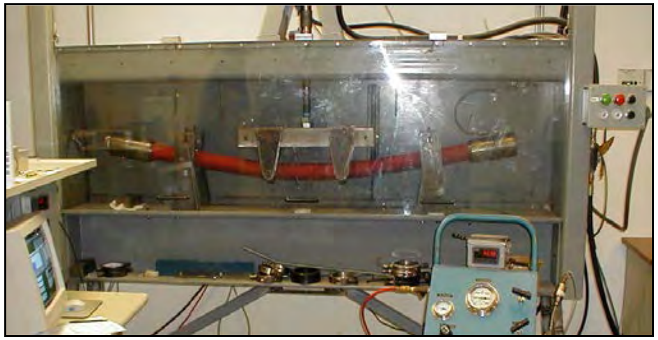
Reinforcement layers provide gas permeation barrier (in addition to polymer liner) but this does not account for the discrepancy between predicted and measured leak rates. We observed a significant amount of H_2 uptake in liner or reinforcement layers or both.

FRP Pipelines Perform Well During Rapid Decompression with Hydrogen

- Rapid decompression test (*a.k.a.* hydrogen "blowdown") based on procedure in Appendix D of API 15S, *Qualification of Spoolable Reinforced Plastic Line Pipe*
  - Pipeline specimens pressurized with H_2 to MAWP (1500 psig), heated to MAWT (60°C), held at MAWP until pipeline structure is saturated with H_2, then depressurized at a rate ≥ 1000 psi/min
  - Post-blowdown: Liner examined for blistering or collapse; specimen tested to verify leak rate has not increased
- Summary of blowdown test results
  - Pipelines with single-polymer liner survived blowdown without liner damage or increased leak rate
  - Pipeline liner of coextruded polymers exhibited separation and collapse under extreme decompression (~5000 psi/min)
- Pipeline connectors – elastomeric sealed and swaged-on have perform well during leak rate and blowdown tests

FRP Pipelines are Chemically Compatible with High-Pressure Hydrogen

- Favorable results obtained in accelerated-aging testing on glass-fiber-reinforced pipelines and pipeline constituent materials immersed in high-pressure hydrogen
  - One-month and eight-month static high-pressure H_2 exposures at elevated temperatures
  - No statistically significant differences between results of qualification tests on air-aged and hydrogen-aged pipeline specimens



  - No statistically significant differences between tested specimens of unexposed, air-exposed and hydrogen-exposed constituent materials (i.e., tensile test specimens of epoxy and liner, and single glass filaments)

H_2 Compatibility of Glass Fibers used as Reinforcement – Tensile Strength

- Accelerated aging of glass fibers in high-pressure H_2 environment, followed by standard tensile testing, used to screen for long-term effects of H_2 on glass fiber reinforcement materials
- Simplified protocol for accelerated aging based on Arrhenius model, with single elevated temperature of 60°C , and no stressors other than H_2 (*i.e.*, no oxygen, water, chemicals, and UV)
- Assumption made that elevated temperature itself does not degrade fibers, but thermal control specimens treated in air tested concurrently with specimens treated in H_2

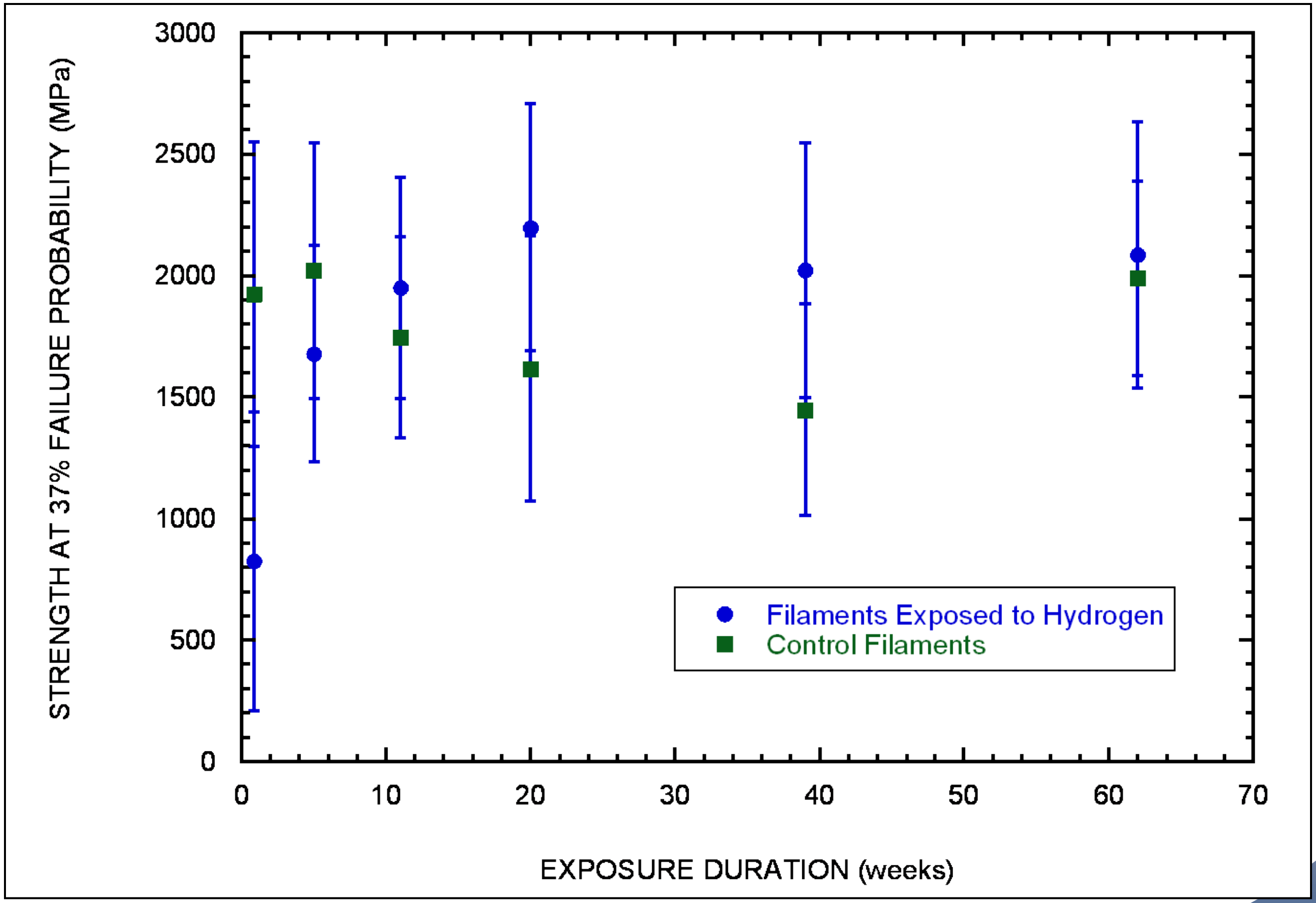
Single glass filaments are used for strength, elongation and modulus measurements

H_2 Compatibility of Glass Fibers Used as Reinforcement – Tensile Strength

- Filaments cut from commercial e-glass
  - Advantex T-30, R25HX22
  - Nominal composition: SiO_2 54 wt%, Al_2O_3 14 wt%, CaO+MgO 22 wt%, B_2O_3 10 wt% and Na_2O+K_2O less than 2 wt%, other materials at impurity levels
- Tensile tests
  - Strength
  - Modulus
  - Elongation

Hydrogen Exposure did not Lessen Tensile Strength of E-Glass Fibers

- Tensile test results obtained on fibers tested at intervals through 62 weeks – No statistically significant changes in tensile properties



Key Knowledge Gaps and Implications

What are the key gaps in our understanding of the performance, durability and safety of composite hydrogen pipelines, and what are the implications for adoption and commercial deployment of the technology for hydrogen delivery applications?

- Fundamental Issues
- State of Knowledge
- Knowledge Gaps

Key Gaps: Fundamental Issues

Composite (FRP) pipeline: Extruded polymer liner reinforced with laminate of glass or aramid fiber rovings cured in epoxy matrix; similar in many respects to construction of Type 4 high-pressure compressed GH2 storage tanks

Issues pertinent to hydrogen delivery:

- Focus on safety, reliability and performance of FRP H_2 pipeline
- Uniform methods for testing and codifying the utilization of FRP H_2 pipelines, pipeline materials and pipeline components
  - Define requirements for H_2 compatibility of FRP pipelines
  - Develop test protocols, establish design limits, implement performance based test methods to demonstrate the acceptance of materials in specific designs
  - Guidelines for testing pipelines and materials in H_2 environments
- Codification and acceptance by regulatory agencies
- Impact of code requirements on hydrogen transmission and distribution costs

Key Gaps: State of Knowledge

- Hundreds of millions of feet of high-pressure FRP pipelines are in service in upstream oil and natural gas gathering operations, water and dense-phase CO_2 well interventions, production and lift system operations, and (recently) installations of natural gas transmission lines via waivers from DOT OPS
- Extensive FRP H_2 pipeline analysis at Oak Ridge National Laboratory and Savannah River National Laboratory has demonstrated technical feasibility
  - H_2 permeation and leakage is low enough to meet DOE targets
  - No degradation due to long-term internal and external H_2 exposures
  - Resistant to catastrophic failures due to accidental and third-party damage
- Prior roadmapping exercise at September 2007 Fuel Cell Technology Program Pipeline Working Group Meeting in Aiken, SC
- Plenitude of worldwide standards for FRP pipelines, joints and fittings…

Key Gaps: State of Knowledge

American Standards Institute

1.ASTM D 1599 - Standard Test Method for Resistance to Short-time Hydraulic Pressure of Plastic Pipe, Tubing, And Fittings
2.ASTM D 2105 - Standard Test Method for Longitudinal Tensile Properties of "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe And Tube
3.ASTM D 2143 - Standard Test Method for Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe
4.ASTM D 2290 - Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe By Split Disk Method
5.ASTM D 2310 - Standard Classification for Machine-made "Fiberglass" (Glass-fiber Reinforced Thermosetting-resin) Pipe
6.ASTM D 2924 - Standard Test Method for External Pressure Resistance of "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe
7.ASTM D 2925 - Standard Test Method for Beam Deflection of "Fiberglass" (Glass fiber-reinforced Thermosetting Resin) Pipe Under Full Bore Flow
8.ASTM D 2992 - Standard Practice for Obtaining Hydrostatic Or Pressure Design Basis for "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe And Fittings
9.ASTM D 2996 - Standard Specification for Filament-wound "Fiberglass" (Glass fiber-reinforced Thermosetting-resin) Pipe
10.ASTM D 2997 - Standard Specification for Centrifugally Cast "Fiberglass" (Glass fiber-reinforced Thermosetting-resin) Pipe
11.ASTM D 3517 - Standard Specification for "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pressure Pipe
12.ASTM D 3567 - Standard Practice for Determining Dimensions "Fiberglass" (Glass fiber-reinforced Thermosetting Resin) Pipe And Fittings
13.ASTM D 3615 - Chemical Resistance of Thermoset Molding Compounds
14.ASTM D 3681 - Standard Test Method for Chemical Resistance of "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe in a Deflected Condition
15.ASTM D 3754 - Standard Specification for "Fiberglass" (Glass-fiber-reinforced thermosetting-resin) Sewer And Industrial Pressure Pipe
16.ASTM D 3840 - Standard Specification for "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe Fittings for Nonpressure Applications
17.ASTM D 4024 - Standard Specification for Machine Made "Fiberglass" (Glass-fiber Reinforced Thermosetting Resin) Flanges
18.ASTM D 4161 - Standard Specification for "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe Joints Using Flexible Elastomeric Seals
19.ASTM D 5365 - Standard Test Method for Long-term Ring-bending Strain of "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pipe
20.ASTM D 5421 - Standard Specification for Contact Molded "Fiberglass" (Glass fiber-reinforced Thermosetting Resin) Flanges
21.ASTM D 5685 - Standard Specification for "Fiberglass" (Glass-fiber-reinforced Thermosetting-resin) Pressure Pipe Fittings

Key Gaps: State of Knowledge

American Petroleum Institute

1.API 15S-Qualification of Spoolable Reinforced Plastic Line Pipe

2.API Spec 5L-Specification for Line Pipe

3.API 15HR-Specification for High Pressure Fiberglass Line Pipe

4.API TR 17TR2-The Ageing of PA-11 in Flexible Pipes

International Organization for Standardization

1.ISO 7370 - Glass fiber reinforced thermosetting plastics (GRP) pipes and fittings; Nominal diameters, specified diameters and standard lengths

2.ISO 7432 - Glass-reinforced thermosetting plastics (GRP) pipes and fittings -- Test methods to prove the design of locked socket-and-spigot joints, including double-socket joints, with elastomeric seals

3.ISO 7510 - Plastics piping systems - Glass-reinforced plastics (GRP) components - Determination of the amounts of constituents using the gravimetric method

4.ISO 7684 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes - Determination of the creep factor under dry conditions

5.ISO 10466 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes – Test method to prove the resistance to initial ring deflection

6.ISO/TR 10465-1 - Underground installation of flexible glass-reinforced thermosetting resin (GRP) pipes; part 1: installation procedures

7.ISO/TR 10465-2 - Underground installation of flexible glass-reinforced thermosetting resin (GRP) pipes - Part 2: Comparison of static calculation methods

8.ISO/TR 10465-3 - Underground installation of flexible glass-reinforced thermosetting resin (GRP) pipes - Part 3: Installation parameters and application limits

9.ISO 10468 - Glass-reinforced thermosetting plastics (GRP) pipes -- Determination of the long-term specific ring creep stiffness under wet conditions and calculation of the wet creep factor

10.ISO 10471 - Glass-reinforced thermosetting plastics (GRP) pipes -- Determination of the long-term ultimate bending strain and the long-term ultimate relative ring deflection under wet conditions

11.ISO 10928 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes and fittings - Methods for regression analysis and their use

12.ISO 14692 - Petroleum and natural gas industries -- Glass-reinforced plastics (GRP) piping – Parts 1-4

13.ISO 14828 - Glass-reinforced thermosetting plastics (GRP) pipes -- Determination of the long-term specific ring relaxation stiffness under wet conditions and calculation of the wet relaxation factor

14.ISO 15306 - Glass-reinforced thermosetting plastics (GRP) pipes -- Determination of the resistance to cyclic internal pressure

Key Gaps: State of Knowledge

British Standards Institute

1.BS 6464 - Specification for reinforced plastics pipes, fittings and joints for process plants

2.BS 7159 - Code of practice for design and construction of glass-reinforced plastics (GRP) piping systems for individual plants or sites

3.BS 8010-2.5 - Code of practice for pipelines - Pipelines on land: design, construction and installation - Glass reinforced thermosetting plastics

Deutsches Institut für Normung

1.DIN 53769-1 - Testing of glass fiber reinforced plastics pipes; determination of the longitudinal shear strength of type B pipe fittings

2.DIN 53769-2 - Testing of glass fiber reinforced plastics pipes; long-term hydrostatic pressure test

3.DIN 53769-3 - Testing of glass fiber reinforced plastics pipes; determination of initial and long-term ring stiffness

4.DIN 53769-6 - Testing of glass fiber reinforced plastics pipes; Testing of pipes and fittings under pulsating internal pressure

5.DIN EN 637 - Plastics piping systems - Glass-reinforced plastics components - Determination of the amounts of constituents using the gravimetric method

6.DIN EN 705 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes and fittings - Methods for regression analyses and their use

7.DIN EN 761 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes - Determination of the creep factor under dry conditions

8.DIN EN 1393 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes - Determination of initial longitudinal tensile properties

9.DIN EN 1447 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes - Determination of long-term resistance to internal pressure

10.DIN EN 1448 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) components - Test methods to prove the design of rigid locked socket- and -spigot joints with elastomeric seals

11.DIN EN 1449 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) components - Test methods to prove the design of a cemented socket- and -spigot joints

12.DIN EN 1450 - Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) components - Test methods to prove the design of bolted flange joints

Knowledge Gaps

- Coordination of testing methods with requirements of H_2 pipeline codes and standards
- Test data on accelerated fatigue due to cyclic pressurization during H_2 service
- Studies done to assess environmental effects on FRP pipeline systems in hydrogen service (all H_2 evaluations to date done in lab settings)
  - Tests conducted with and without water exposure
  - Tests conducted on potential impacts of geotechnical phenomena
  - Tests conducted with real third-party damage
  - Microanalysis and chemical analysis to determine effects of environment on pipeline structure
  - Hydrogen delivery “test loop” that includes all the delivery infrastructure relevant to full pipeline emplacement and operation (*i.e.*, a few miles of pipeline with fittings, compressors, etc., in varying terrains and environments)
  - Harmonization of results obtained in the lab and in field installation

Knowledge Gaps

- Gas purity requirements and pipeline gas purity data
- Expanded knowledge of H_2 performance in commercial products -- Testing to date focused mainly on FRP pipeline products offered by two domestic manufacturers

Other Drivers for Hydrogen and Composites

Near Term

- Push to reduce station cost likely means in the near-term that incoming tube trailers will need to deliver higher pressure gas and possibly incorporate cascade functions (i.e. our information suggests that mobile re-fuelers might make the most sense in early markets)
  - High pressure (hydrogen) effects on composite materials
  - Possible concerns with H_2 "pooling" or traps and depressurization effects (not only in composites but monolithic polymeric materials)
  - Combined dynamic effects (i.e. effects of vibration, etc. from on-road transport)
- Operation lifetime limits with current diaphragm (station) compressors appear to be anecdotally related to stop/start conditions (cavitation damage on diaphragm membranes) and mechanical fatigue (but not embrittlement). What are possible options?
- Need for prioritization (How long the focus will be on CHG is unknown)

Other Drivers

Longer Term

- Potential for thermal cycle fatigue with LH_2 delivery – again focus is on future station operations

Acknowledgements

- Fiberspar, Polyflow, Flexpipe
  - Manufacturers of fiber-reinforced polymer pipelines
  - Provided pipeline specimens, testing, advisement
- Akema, Ticona, Dow Chemical/Polypipe, Lincoln Composites
  - Polymer manufacturers, polymer end-users
  - Provided specimens of polymeric barriers for testing as potential pipeline liner materials
- Fluoro-Seal
  - Advisement on surface treatments to decrease permeation rates
  - Pending: fluorination of polymer specimens
- Savannah River Laboratory
  - Collaboration on hydrogen compatibility studies of FRP pipelines and constituent materials
  - Collaboration with ASME on codification of composite hydrogen pipelines
- Pipeline Working Group and Delivery Tech Team
  - Provide project review and guidance
  - Information clearinghouse

ASME STANDARDS TECHNOLOGY, LLC

Your R&D Partner

ASME Introduction to Composite Pressure Vessel Standards Activities

Research Supporting the Development of ASME Standards for Hydrogen Infrastructure

Composite Conference 2012 - Las Cruces, NM

Gita Sheth

August 14, 2012

Introduction to ASME

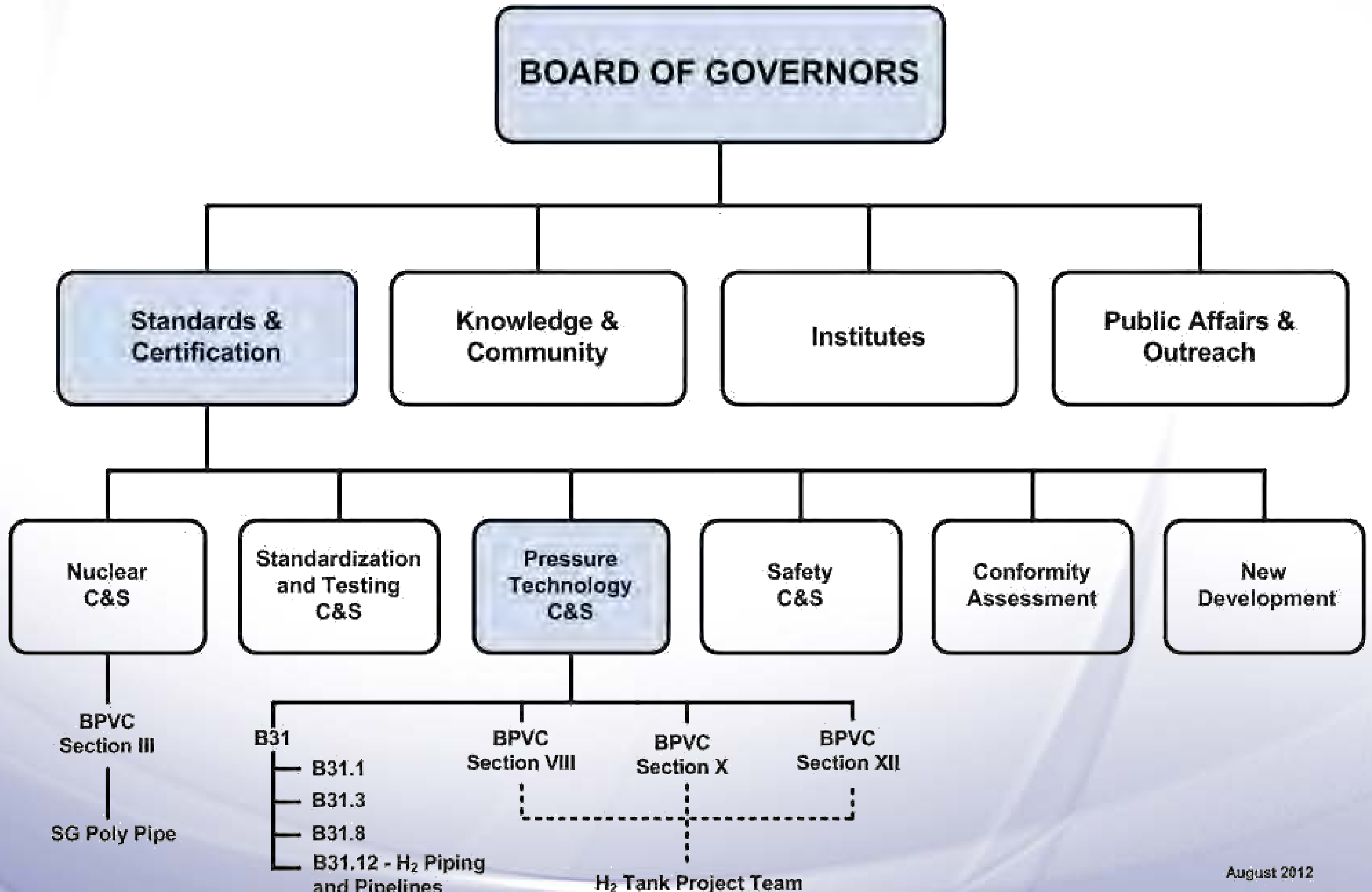
- Educational and technical society of mechanical engineers
- Not-for-profit organization founded in 1880
- 125,000 members worldwide, including 28,000 student members
- Staff of over 300; headquarters in New York City
- Conducts large technical publishing operations
- Holds numerous technical conferences worldwide
- Offers professional development and continuing education courses
- Sets internationally recognized industrial and manufacturing codes and standards that enhance public welfare and safety

ASME Standards & Certification

- Celebrating 125+ years; first standard issued 1884
- 50 consensus committees
- 700 total committees
- 530 standards
- 5 Supervisory Boards
- 4,800 Volunteers from manufacturing, operations, government, etc. (600+ international and rising)
- ~30 technical staff
- ASME Standards accepted for use in >100 Nations
- Administer over 40 U.S. TAGs to ISO
- 10 Conformity Assessment programs

ASME Organization

ASME STANDARDS TECHNOLOGY, LLC



August 2012

Standards Development

ASME STANDARDS TECHNOLOGY, LLC

- ASME's Voluntary Consensus Process
  - Openness, balance of interests, transparency, consensus, and due process
- American National Standards Institute (ANSI) accredited procedures
- Compliance with World Trade Organization (WTO) Technical Barriers to Trade (TBT) principles for international standards development
  - Transparency, openness, impartiality and consensus, effectiveness and relevance, coherence, and development dimension

Standards Development

ASME STANDARDS TECHNOLOGY, LLC

- Standards development steps
  - Initiate Standards Action
  - Prerequisite technical work
  - Draft standard – project team
  - Distribute to cognizant groups for review and comment
  - Standards Committee approval
  - Public review
  - Supervisory Board approval
  - ANSI approval

National Technology Transfer and Advancement Act of 1995

- Signed into law on March 7, 1996 as PL 104-113
- Continues policy changes initiated under OMB A-119
  - Federal Participation in the Development and Use of Voluntary Standards
- Relative to Standards:
  - Generally requires Federal agencies and departments to use technical standards developed or adopted by voluntary consensus standards bodies
  - Directs Federal agencies and departments to consult with and participate in voluntary consensus bodies developing technical standards

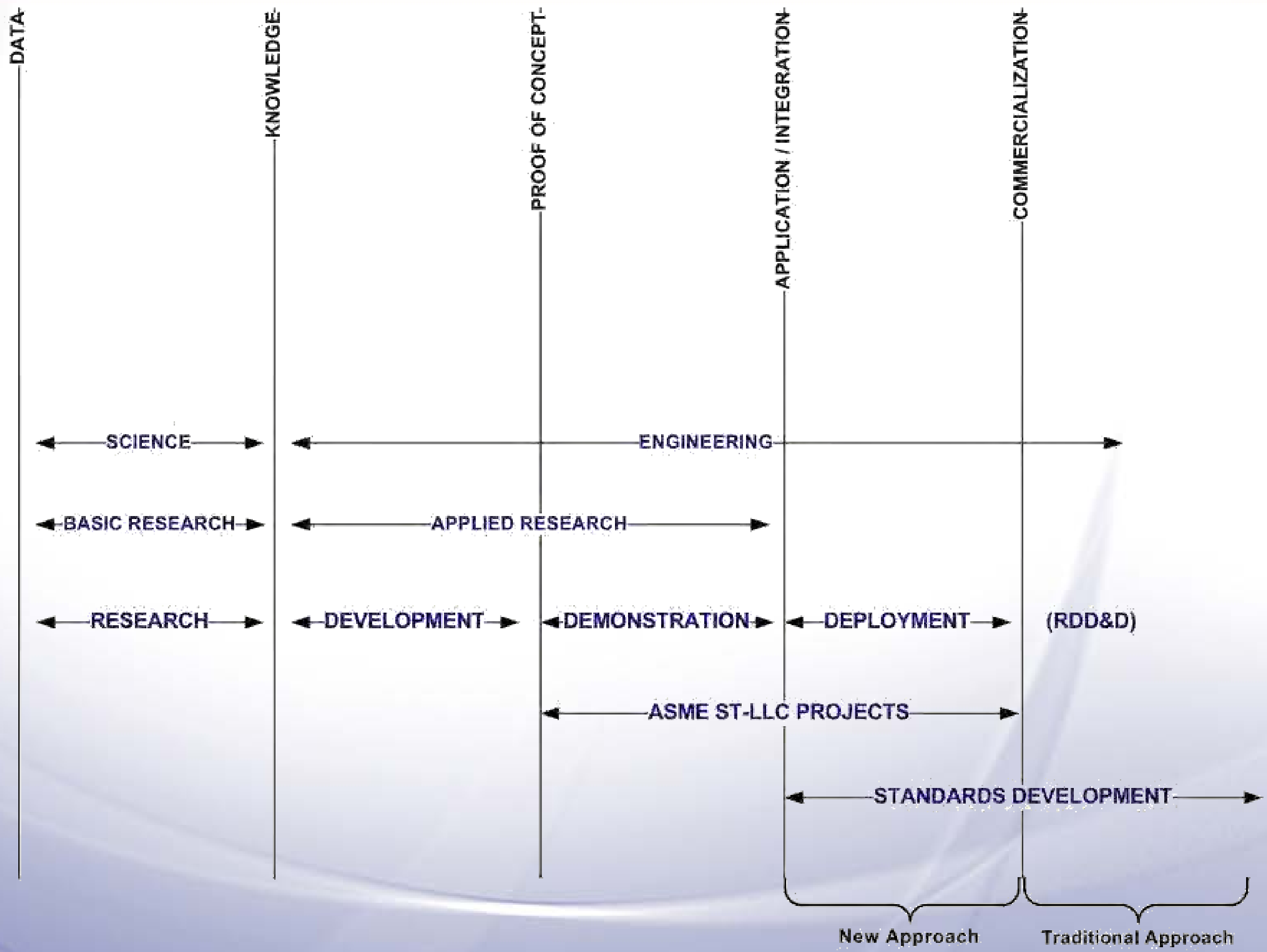
ASME Standards Technology, LLC (ASME ST-LLC)

- Established in 2004
- Separate legal entity; not-for-profit
- Mission:
  - Meet needs of industry and government to advance application of technology
  - Advance standardization needs of emerging and newly commercialized technology
  - Provide R&D needed to establish and maintain technical relevance of codes and standards
- Contracting and Project Office for ASME S&C research
- Deliver results directly into S&C development process
- Publication and dissemination of research results
- Reduce standards development time

ASME ST-LLC Approach

- Standards advance commercialization of new technology
- Standards development supports new regulations
- ASME ST-LLC projects anticipate standards needs and bridge gaps between technology development and standards development
- ASME S&C involvement in R&D projects helps ensure results will be relevant to standards committees
- Directed R&D focuses limited resources on priority areas
- Collaborative R&D projects minimize individual investment while maximizing benefits
- International partnerships between government, industry, and academia help build consensus leading to technically relevant standards

Technology Development



Commercialization Through Standards Development

ASME STANDARDS TECHNOLOGY, LLC

- Commercialization of technology is critical to meeting many global challenges
- Lack of standards can create barriers to commercialization
- Research can provide the technical basis without limiting innovation
- Adoption of consensus standards increases public confidence
- Standards development complements public/private initiatives
  - Research and development
  - Technology demonstrations
  - Infrastructure construction
  - Engage subject matter expertise from other sectors
  - Provide a forum for broad collaboration between government and industry stakeholders
  - Support establishment of new regulations
  - Enable rapid/transportable workforce development
  - Facilitate business and trade

Case Study – Hydrogen Infrastructure

ASME STANDARDS TECHNOLOGY, LLC

- Nov'02 - ASME was approached by industry and government stakeholders to investigate standards needs for hydrogen infrastructure applications up to 15,000 psig.
- At the time relevant ASME Codes and Standards included:
  - Tanks:
    - BPVC Section VIII
      - Division 1 – Pressure Vessels
      - Division 2 – Alternative Rules
      - Division 3 – High Pressure Vessels)
      - Code Case 2390 (VIII-3) - Composite Reinforced Pressure Vessels (issued Oct'02)
    - BPVC Section X - Fiber-Reinforced Plastic Pressure Vessels
    - BPVC Section XII - Rules for Construction of Transport Tanks
  - Piping and Pipelines:
    - B31.1 - Power Piping
    - B31.3 - Process Piping
    - B31.8 - Gas pipelines
    - B31.8S - Managing gas pipeline integrity
  - Fuel Cells:
    - PTC 50 - Fuel Cell Power Systems Performance (issued Jul'02)

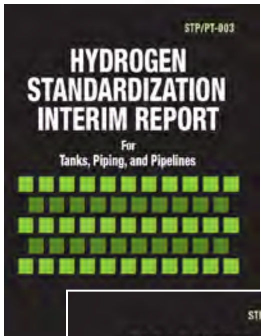
Case Study – Hydrogen Infrastructure

ASME STANDARDS TECHNOLOGY, LLC

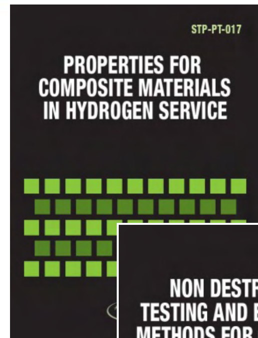
- Nov’02 - formed ASME Hydrogen C&S Steering Committee
- Jan’03 - engaged with DOE, NREL, and other SDOs
  - National Hydrogen and Fuel Cell Codes & Standards Coordinating Committee
- May’03 - ASME H_2 C&S Task Forces formed
  - H_2 Storage and Transport Tanks
  - Small Portable H_2 Tanks
  - H_2 Piping and Pipelines
- May’04 - ASME PTCS Project Teams formed and started standards development activities
  - Hydrogen Piping and Pipelines (now B31.12 Standards Committee)
  - Hydrogen Tanks
- Jul’04 - Sep’09 - conducted related research in parallel with standards development activities
  - NREL Sponsored Projects:
    - H_2 Standardization Interim Report (Jul’04-Sep’05)
    - Design Margins for H_2 Tanks, Properties of Composite Materials in H_2 Service (Jul’05-Oct’05)
    - Data Supporting Composite Tank Standards Development (Sep’06-Sep’07)
    - Flaw Testing for Composite Pressure Vessels (Dec’08-Sep’09)
  - NCMS/ Industry Sponsored Project:
    - Non Destructive Testing and Evaluation Methods for Composite H_2 Tanks (Apr’06-Apr’07)
  - ASME Sponsored Projects:
    - Design Margin Guidelines for H_2 Piping and Pipelines (Aug’05-Jul’07)
    - Guidelines for In-service Inspection of Composite Pressure Vessels (Feb’08-Feb’09)

Case Study – Hydrogen Infrastructure

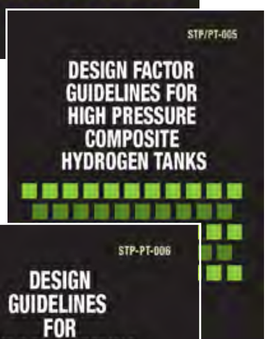
ASME STANDARDS TECHNOLOGY, LLC



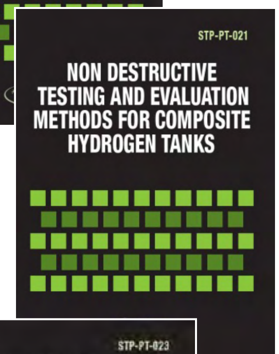
STP-PT-003 – Hydrogen Standardization Interim Report



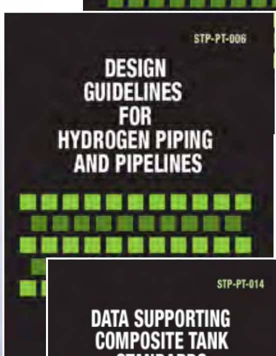
STP-PT-017 – Properties for Composite Materials in Hydrogen Service



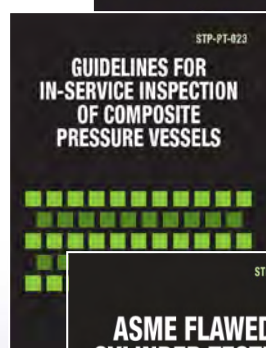
STP-PT-005 – Design Factor Guidelines for High-Pressure Composite H_2 Tanks



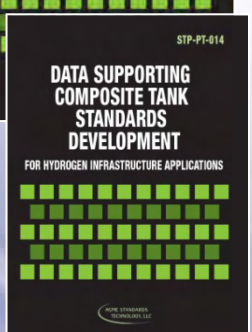
STP-PT-021 – Non Destructive Testing and Evaluation Methods for Composite Hydrogen Tanks



STP-PT-006 – Design Guidelines for Hydrogen Piping and Pipelines



STP-PT-023 – Guidelines for In-service Inspection of Composite Pressure Vessels



STP-PT-014 – Data Supporting Composite Tank Standards Development

STP-PT-043 – ASME Flawed Cylinder Testing

Case Study – Hydrogen Infrastructure

ASME STANDARDS TECHNOLOGY, LLC

- Resulting new standards:
  - Dec’06: Code Case 2563, AA 6061 construction (VIII-3)
  - Apr’07: Code Case 2569, SA-372 Steel Construction (VIII-3)
  - Jul’07: Section VIII, Division 3, Article KD-10 - special requirements for fracture resistance of all-steel vessels
  - Aug’07: Code Case 2579 - Hoop-wrapped Composite Reinforced Pressure Vessels with Welded Liners for Gaseous H_2 Service (VIII-3)
  - Mar’09: ASME B31.12 – Hydrogen Piping and Pipelines
  - Jul’10: Section X Mandatory Appendix 8 - Class III Vessels with Non-Load Sharing Liners for Gaseous Hydrogen in Stationary Service
- Timeline: Nov’02 - Jul’10 (~7 years)

Supporting ASME Strategic Initiatives

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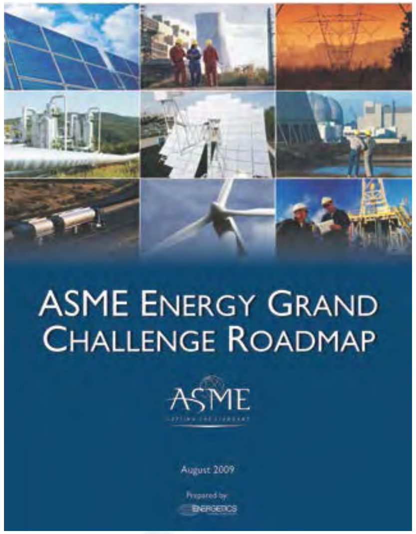
- Energy Grand Challenge
  - "Develop ...codes and standards...to support energy technology innovation and commercialization"
  - "*Identify standards needs...* perform standards gap analyses and develop comprehensive standards development plans..."
  - "High-priority energy technology areas include wind, solar, hydrokinetics, geothermal, biofuels, hydrogen, energy efficiency, carbon capture and storage, and energy storage."
  - "...complements public-private R&D, technology demonstration, and infrastructure construction programs."
- Workforce Development
- Globalization



Overview of ASTM Standardization Efforts Related to COPVs

Jess M. Waller
NASA-JSC White Sands Test Facility

Session I:

Standards, Codes and Regulations (Common Protocols)

Composite Conference 2012

Las Cruces, NM

Tuesday, August 14, 2012

COPV Standards

- No less than half a dozen voluntary consensus organizations (VCOs) are actively involved in promulgation of standards directly and indirectly related to COPVs
- ASTM standards consist of Practices, Test Methods, Guides, Terminology, and Specifications:
  - *Practice*: tells how to perform a test
  - *Test Method:* tells how to produce a numerical result, often used as an accept-reject criterion
  - *Guide*: general instruction and overview
  - *Terminology*: establishes consistent naming conventions and definitions
  - *Specification*: establishes uniform material and component properties
- ASTM standards usually focus on a technique, but can focus on material or component type, e.g., a COPV, subject to testing using a variety of techniques

Voluntary Consensus Organization Standards Relevant to COPVs
(non-inclusive list)

1. **AIAA/ANSI**
   - S-080 Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
   - S-081 Space Systems - Composite Overwrapped Pressure Vessels (COPVs)
   - NGV2-2007 American National Standard for Natural Gas Vehicle Containers
2. **ASME**
   - Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels, Appendix 8-620 Supplementary Examination Requirements
   - STP-PT-021 Non Destructive Testing and Evaluation Methods for Composite Hydrogen Tanks
   - STP-PT-023 Guidelines for In-service Inspection of Composite Pressure Vessels
3. **ASTM**

D30
Composite Materials

   - D1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases
   - D2585 Test Method for Preparation and Tension Testing of Filament-Wound Pressure Vessels
   - D2990Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics
   - D3039 Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials
   - D3878 Standard Terminology for Composite Materials
   - D4018 Properties of Continuous Filament Carbon and Graphite Fiber Tows
   - D4762 Guide for Testing Polymer Matrix Composite Materials
   - D5687 Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation
   - D7337 Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars

D20
Plastics

   - D2343 Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics
   - D3299 Specification for Filament-Wound Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks

D35
Geotextiles

   - D5262 Test Method for Evaluating the Unconfined Tension Creep and Creep Rupture Behavior of Geosynthetics
   - D6992 Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method

Voluntary Consensus Organization Standards Relevant to COPVs
(non-inclusive list)

5. ASTM (cont.)

E07
Nondestructive Testing

- E1067 Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels
- E1118 Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)
- E1419 Test Method for Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission
- E1736 Practice for Acousto-Ultrasonic Assessment of Filament-Wound Pressure Vessels
- E1930 Practice for Examination of Liquid-Filled Atmospheric and Low-Pressure Metal Storage Tanks Using Acoustic Emission
- E2191 Test Method for Examination of Gas-Filled Filament-Wound Composite Pressure Vessels Using Acoustic Emission
- E2478 Practice for Determining Damage-Based Design Stress for Glass Fiber Reinforced Plastic (GFRP) Materials Using Acoustic Emission
- E2533 Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications
- E2581 Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications
- E2661 Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications
- E2862 Practice for Probability of Detection Analysis for Hit/Miss Data

6. CGA

- Pamphlet C-6.2, Standard for Visual Inspection and Requalification of Fiber Reinforced High Pressure Cylinders
- Pamphlet C-6.4, Methods for Visual Inspection of AGA NGV2 Containers

7. ISO

- 6046 Gas cylinders - Seamless steel gas cylinders - Periodic inspection and testing
- 10461 Gas cylinders - Seamless aluminium-alloy gas cylinders - Periodic inspection and testing
- 11119-1 Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Part 1: Hoop wrapped fibre reinforced composite gas cylinders and tubes up to 450 l
- 11119-2 Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Part 2: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with load-sharing metal liners
- 14623 Space Systems - Pressure Vessels and Pressurized Structures - Design and Operation

ASTM Committee E07

Flat Panel and COPV Standards

Accomplishments Since 2007

Designation: E 2580 – 07

Standard Practice for
Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2581 – 07

Standard Practice for
Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for
Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

Accomplishments Since 2007

Designation: E 2662 – 09

Standard Practice for
Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2533 – 09

Standard Guide for
Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for
Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

Item Registered for COPV Overwrap Standard in 2010

http://www.astm.org/DATABASE.CART/WORKITEMS/WK29034.htm

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ASTM WK29034

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

Developed by Subcommittee: E07.10 | Committee E07 Home | Contact Staff Manager

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Work Item Status:
Date Initiated: 06-01-2010
Technical Contact: Jess Waller

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

1. Scope

1.1 This Practice discusses nondestructive testing (NDT) methods for detecting flaws, defects, and accumulated damage in filament wound pressure vessels, also known as composite overwrapped pressure vessels (COPVs), used in aerospace applications. In general, these vessels have metal liner thicknesses less than 2.3 mm (0.090 in.), and fiber loadings in the composite overwrap greater than 60 percent by weight. 1.2 Although this Practice focuses on COPVs used at ambient temperature, it also has relevance to 1) composite pressure vessels (CPVs), 2) monolithic metallic pressure vessels, and 3) COPVs and CPVs used at cryogenic temperatures. 1.3 This Practice applies to 1) low pressure COPVs used for storing liquid propellants at maximum allowable working pressures (MAWPs) up to 35

Item Registered for COPV Liner Standard in 2010

http://www.astm.org/DATABASE.CART/WORKITEMS/WK29068.htm

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ASTM WK29068

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

Developed by Subcommittee: E07.10 | Committee E07 Home | Contact Staff Manager

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1. Scope

1.1 This Practice discusses nondestructive testing (NDT) methods for detecting defects and flaws in thin-walled metallic pressure vessels (PVs) and composite overwrapped pressure vessels (COPVs) used in aerospace applications. In general, these COPVs have metal liner thicknesses less than 2.3 mm (0.090 in.) and a filament wound composite overwrap. 1.2 Although this Practice focuses on PVs and COPVs used at ambient temperature, it also has relevance to a) composite pressure vessels (CPVs), and b) COPVs and CPVs used at cryogenic temperatures. NDT of the composite overwrap of COPVs is beyond the scope of the Practice, however, a general overview of applicable NDT methods is provided in Guide E2533. 1.3 This Practice applies primarily to high pressure COPVs used for storing compressed gases

Work Item Status:

Date Initiated: 06-02-2010

Technical Contact: Jess Waller

Status: Draft Under Development

Standards Tracker

Standards Subscriptions

ASTM E07 Standards for NDE of Composites 2005 to present §

2005

Flat Panel Composites

2010

2011

COPVs

2012

5-year re-approval of E 2580, E 2580 and E 2581

2013

POD

Metal & Brittle Matrix Composites

Test Methods for Accept-Reject

Designation: E 2533 – 09

Standard Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

Designation: E 2580 – 07

Standard Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

Designation: E 2581 – 07

Standard Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2662 – 09

Standard Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

Nondestructive Evaluation of Flat Panel Composites: Standard Practices and Guide

ASTM WK29034

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

ASTM WK29068

(What is a Work Item? / How to Input to a Work Item)

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

Nondestructive Evaluation of COPVs: Standard Practices, Feasibility of Guide

§ funding for technical oversight provided by the NASA NDE Working Group (NNWG) and NASA Technical Standards Program (NTSP)

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November/December 2009

UpDate

Flat Panel Composites

E-mail Print

NASA White Sands Test Facility technicians perform radiographic inspection on a filament wound pressure vessel.

A series of standards on nondestructive inspection and examination of aerospace composites has been developed under the jurisdiction of ASTM International Committee E07 on Nondestructive Testing. Several years ago, with impetus and input from representatives of the U.S. National Aeronautics and Space Administration, a task group on NDE for aerospace composites was formed under Subcommittee E07.10 on Specialized NDT Methods.

The task group, chaired by George Matzkanin from the Texas Research Institute, Austin, was established to foster the development of standards for NDE of aerospace composites. A recently published standard, ASTM E2533, Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications, was developed under the guidance of task group and E07.10 subcommittee member Jess Waller, NASA White Sands Test Facility. This guide helps engineers select appropriate nondestructive testing methods to examine and characterize aerospace composites.

In addition to the guide, several standard practices have been developed and published to document and establish control requirements of current established industry practices so that these standards can be specified in contracts. One such practice is the new standard ASTM E2662, Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications, developed under the guidance of task group member John Ellegood, Lockheed Martin Space Systems Co. This standard was developed under the jurisdiction of Subcommittee E07.01 on Radiology (X and Gamma) Method.

ASTM E2662 provides process control requirements for film and digital radiography of aerospace composite panels. "Using ASTM E2662 will improve accuracy and reliability of radiographic examinations for these low density structures," says Ellegood, a staff quality engineer and Level 3 radiographer. "Often, examinations are not performed at optimal levels due to inadequate experience and lack of requirements."

In addition to the guide, several standard practices have been developed and published to document and establish control requirements of current established industry practices so that these standards can be specified in contracts. One such practice is the new standard ASTM E2662, Practice for Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications, developed under the guidance of task group member John Ellegood, Lockheed Martin Space Systems Co. This standard was developed under the jurisdiction of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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Ellegood, who also serves on the Leadership Committee of the Federal Working Group on Industrial Digital Radiography, says that NASA, the U.S. Department of Defense and manufacturers of aerospace and aircraft structures using lightweight composite panels will be the primary users of ASTM E2662.

Three additional practices developed under the guidance of the task group and published earlier are:

- E2580, Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications;
- E2581, Practice for Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications; and
- E2582, Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications.

The task group is now moving forward with the development of proposed guides and practices for the inspection/examination of more complex composite components, such as composite overwrapped pressure vessels. All interested parties, including engineers working in nondestructive testing, materials and aerospace, are welcome to contribute to the ongoing development of these proposed standards.

CONTACT

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(E2662) John Ellegood, Lockheed Martin Space Systems Co., Denver, Colo.

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January/February 2010
UpDate

Phased Arrays, Aerospace Applications, Digital Imaging

E-mail Print

ASTM International Committee E07 on Nondestructive Testing has recently approved three new standards on phased arrays, polymer matrix composites for aerospace applications and digital imaging. The committee will be meeting in Plantation, Fla., Jan. 24-28, and welcomes participation in its standards developing activities.

Ultrasonic Methods

Thousands of portable phased array units, used for weld inspections, have now been sold worldwide. There are many benefits to these devices, including speed, cost, imaging, flexibility and setups, along with no radiation, licensing or contamination. Despite these advantages, there was not a universal inspection procedure for phased array inspection of welds. A new standard, E2700, Practice for Contact Ultrasonic Testing of Welds Using Phased Arrays, provides such an inspection test.

E2700 was developed by Subcommittee E07.06 on Ultrasonic Method. According to Michael Moles, senior technology manager, Olympus NDT, and an E07 member, E2700 will be most useful to inspection companies that need to write and follow procedures and to end users and regulators who need to establish practices for the inspection companies.

"E2700 will be very helpful as it covers the relevant aspects for most weld inspections, so details will not be ignored or forgotten," says Moles.

Specialized NDT Methods

A new guide gives an introductory overview that describes how mature and established nondestructive testing methods that are routinely used by industry are applied specifically to the characterization of polymer matrix aerospace composites. E2533, Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications, is under the jurisdiction of Subcommittee E07.10 on Specialized NDT Methods.

"The practical value of E2533 is that the major, accepted nondestructive testing methods are covered in a single document," says Jess Waller, a materials scientist at GeoControl Systems Inc. and a member of E07.10. "Primary users of the standard will be the aerospace industry and its primary contractors in building spacecraft and launch vehicles for present and future NASA programs." This includes all government and industrial entities involved in:

- Product and process design and optimization;
- Online process control;
- After manufacture inspection;
- In-service inspection; and
- Health monitoring of polymer matrix aerospace composites.

Waller notes that E2533 can be used to select an appropriate nondestructive test depending on the type of flaw a user is trying to detect and to provide instruction on where in the life cycle of a composite material or component a particular test can be used. In addition, the advantages and limitations of each of the major nondestructive tests are discussed, with reference to relevant standards.

The aerospace industry will use new standards approved by Committee E07 on Nondestructive Testing in the development of future spacecraft.

Digital Imaging and Communication in Nondestructive Evaluation

A new standard developed by Subcommittee E07.11 on Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) will fill a need in the nondestructive testing industry for a transparent and industry standard data format with which to store digital inspection data.

E2663, Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Ultrasonic Test Methods, will be used by manufacturers to develop ultrasonic test equipment that communicates and stores inspection data in a nonproprietary format that will be used for decades.

"Critical national and commercial infrastructure requires long-term data management solutions for inspection data," says Patrick Howard, GE Aviation, who notes that, in the United States, nuclear power plants are typically licensed for 40 years but can obtain an operating extension for an additional 20 years.

"Over such long time periods, inspection equipment is replaced with new models, and equipment vendors may go out of business while the need to access the data acquired with the equipment remains," says Howard. "There is a need to promote interoperability as inspection equipment is modernized to provide long-term data access."

E2663 will serve as a companion standard to E2339, Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE). While E2339 addresses digital data transmission and storage for all nondestructive evaluation modalities, E2663 addresses digital data transmission and storage specific to ultrasonic testing.

Howard also notes that E07.11 is now at work on the following related proposed practices:

- WK17435, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for X-Ray Computed Tomography (CT) Test Methods;
- WK17436, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Digital Radiographic (DR) Test Methods;
- WK20537, Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Eddy Current Test Methods; and

Current POD Activities/Resources

ASTM E07.10:

http://www.astm.org/Standards/E2862.htm

http://www.nxtbook.com/nxtbooks/astm/sn_20120708/#/54

Designation: E2862 – 12

Standard Practice for Probability of Detection Analysis for Hit/Miss Data[1]

This standard is issued under the fixed designation E2862; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice defines the procedure for performing a statistical analysis on nondestructive testing hit/miss data to determine the demonstrated probability of detection (POD) for a specific set of examination parameters. Topics covered include the standard hit/miss POD curve formulation, validation techniques, and correct interpretation of results.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1316 Terminology for Nondestructive Examinations

2.2 *Department of Defense Handbook:*

MIL-HDBK-1823A Nondestructive Evaluation System Reliability Assessment[3]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *analyst, n*—the person responsible for performing a POD analysis on hit/miss data resulting from a POD examination.

3.1.2 *demonstrated probability of detection, n*—the calculated POD value resulting from the statistical analysis on the hit miss data.

3.1.3 *false call, n*—the perceived detection of a discontinuity that is identified as a find during a POD examination when no discontinuity actually exists at the inspection site.

3.1.4 *hit, n*—an existing discontinuity that is identified as a find during a POD demonstration examination.

3.1.5 *miss, n*—an existing discontinuity that is missed during a POD examination.

3.1.6 *probability of detection, n*—the fraction of nominal discontinuity sizes expected to be found given their existence.

3.2 *Symbols:*

3.2.1 a—discontinuity size.

3.2.2 a_p—the discontinuity size that can be detected with probability p.

3.2.2.1 *Discussion*—Each discontinuity size has an independent probability of being detected and corresponding probability of being missed. For example, being able to detect a specific discontinuity size with probability p does not guarantee that a larger size discontinuity will be found.

3.2.3 $a_{p/c}$—the discontinuity size that can be detected with probability p with a statistical confidence level of c.

3.2.3.1 *Discussion*—$a_{p/c}$ is calculated by applying a statistical uncertainty bound to a_p. The uncertainty bound is a function the amount of data, the scatter in the data, and the specified level of statistical confidence. The resulting value represents how large the discontinuity with POD equal to p could be when uncertainty associated with estimating a_p is accounted for. Hence $a_{p/c} > a_p$. Note that POD is equal to p for both $a_{p/c}$ and a_p. a_p is based solely on the hit/miss data resulting from the examination and represents a snapshot in time, whereas $a_{p/c}$ accounts for the uncertainty associated with limited sample data.

[1] This practice is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

Current edition approved Jan. 15, 2012. Published February 2012. DOI:10.1520/E2862-12.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, http://dodssp.daps.dla.mil.

update

E07/NONDESTRUCTIVE TESTING

Detection Analysis for Hit/Miss Data

A new ASTM International standard provides the necessary background and describes the step-by-step process for analyzing nondestructive testing hit/miss data resulting from a probability of detection examination, including minimum requirements for validating the resulting POD curve.

The new standard, E2862, Practice for Probability of Detection Analysis for Hit/Miss Data, has been developed by Subcommittee E07.10 on Specialized NDT Methods, part of ASTM International Committee E07 on Nondestructive Testing.

"A probability of detection demonstration test and analysis is the best available method for quantifying the detection capability of a nondestructive testing system," says Jennifer R. Brown, senior statistician, Pratt and Whitney Rocketdyne, and a member of E07.10. "However, a POD demonstration test and analysis can be a pointless exercise without a basic understanding of the NDT system as well as a general understanding of the underlying statistical method on which the POD analysis is based."

E2862 will be useful to anyone who is responsible for performing a probability of detection analysis on hit/miss data resulting from a POD examination.

Brown notes that E2862 will provide this understanding and will be useful to anyone who is responsible for performing a probability of detection analysis on hit/miss data resulting from a POD examination as well as those who are recipients of, and base decisions on, the results of such an analysis. The U.S. National Aeronautics and Space Administration requires probability of detection demonstration tests on nondestructive testing systems that are used evaluate fracture critical hardware.

To purchase ASTM standards, visit www.astm.org and search by the standard designation, or contact ASTM Sales (phone: 877-909-ASTM; sales@astm.org).

CONTACT Technical Information: Jennifer R. Brown • Pratt and Whitney Rocketdyne • West Palm Beach, Fla. • Phone: 561-796-2230 • Email: jennifer.brown@pwrutc.com ■ ASTM Staff: Kathleen McClung • Phone: 610-832-9717 • Email: kmcclung@astm.org ■ Upcoming Meeting: Jan. 27-31, 2013 • Plantation, Fla.

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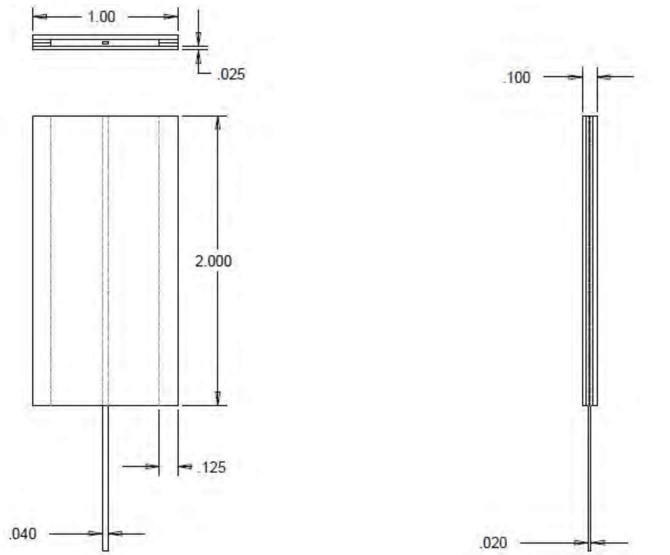
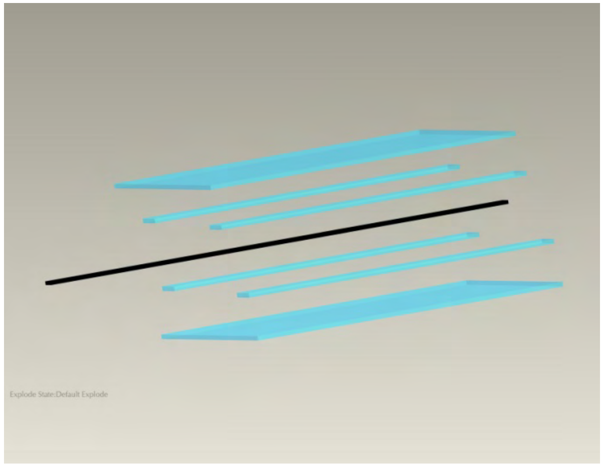
Quick Look at ASTM Standards
Used at WSTF
for Fiber, Composite Tow, and COPV Testing

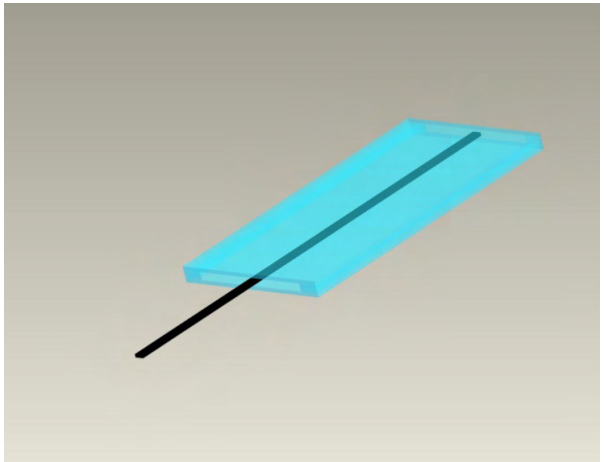
Composite Tow Tests

COPV Materials-of-Construction

Tabbing: shear strength of epoxy and bonded grip length are important variables[§]







$$L_{min} = F^{tu}h/2F^{su}$$

where:

- L_{min} = minimum required bonded tab length, mm [in.];
- F^{tu} = ultimate tensile strength of coupon material, MPa [psi];
- h = coupon thickness, mm [in.]; and
- F^{su} = ultimate shear strength of adhesive, coupon material, or tab material (whichever is lowest), MPa [psi].

§ ASTM D 2343, *Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics,* American Society for Testing and Materials, West Conshohocken, PA (2009).

ASTM D 3039, *Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials*, American Society for Testing and Materials, West Conshohocken, PA (2008).

Fiber Composite Tow Tensile Tests

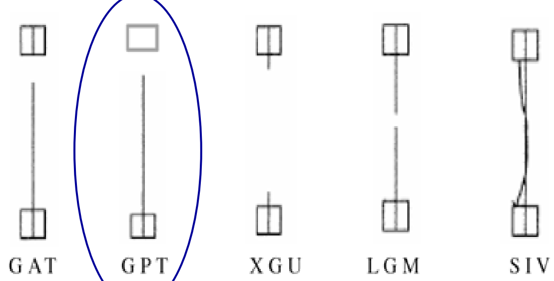
COPV Materials-of-Construction

Establish typical fiber, and composite tow and laminate failure modes

Common failure modes:

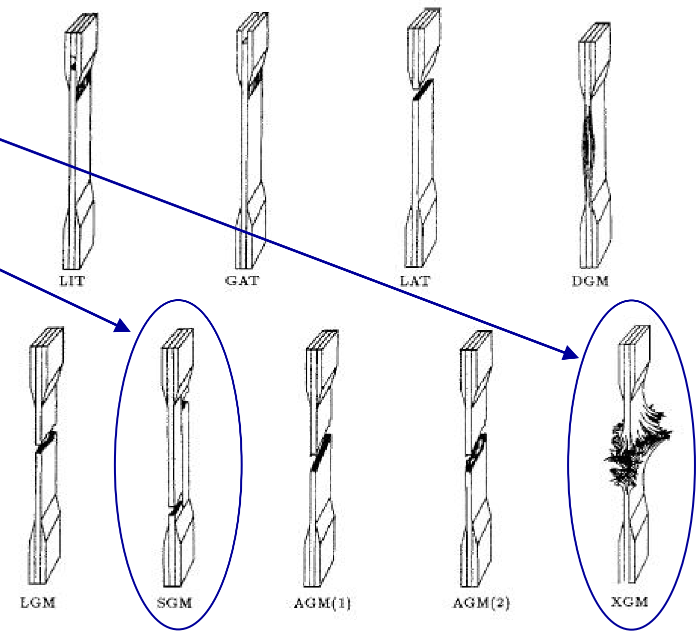
1. explosive failure (XGM)
2. long splitting (SGM)
3. pull-out (GPT)

ASTM D 4018



First Character		Second Character		Third Character	
Failure Type	Code	Failure Area	Code	Failure Location	Code
Grip/Tab	G	Inside Grip/Tab	I	Bottom	B
Lateral	L	At Grip/Tab	A	Top	T
Long Splitting	S	<1 W from grip/tab	W	Middle	M
(fiber pullout)		Gage	G	Various	V
Explosive	X	Tab Pullout	P	Unknown	U
Other	O	Various	V		
		Unknown	U		

ASTM D 3039



First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xyz)
long. Splitting	S
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

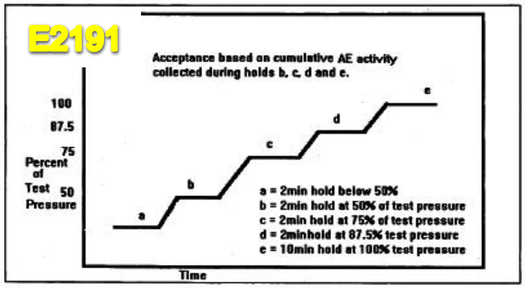
§ ASTM D 4018: *Properties of Continuous Filament Carbon and Graphite Fiber Tows*, American Society for Testing and Materials, West Conshohocken, PA (2011).

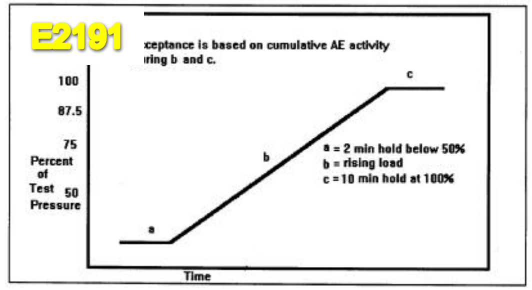
ASTM D 3039, *Test Method for Determining Tensile Properties of Polymer Matrix Composite Materials*, American Society for Testing and Materials, West Conshohocken, PA (2008).

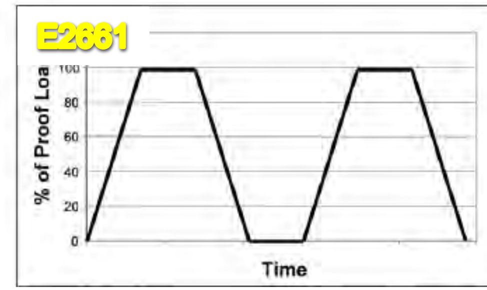
Pressure Schedules

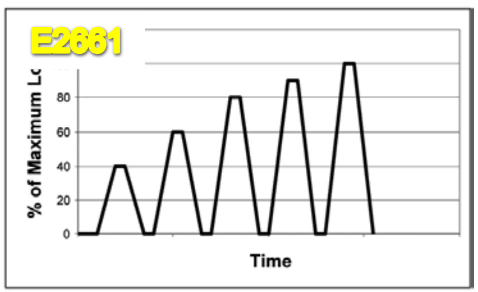
Choice Depends on Data Sought and COPV Application

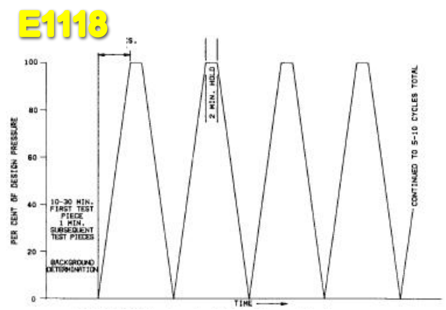
Possible pressure schedules for analytical testing of COPVs:

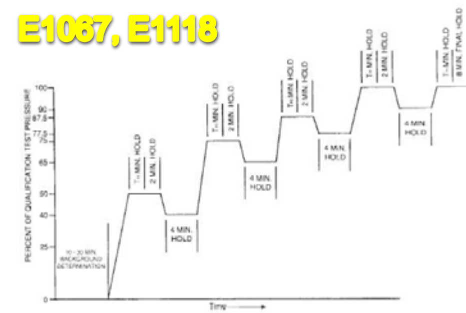


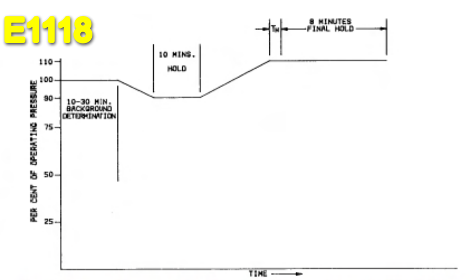












NOTE 1—Diameter to thickness ratio (d/t) ≥ 16, $T_H = 2$ min. Diameter to thickness ratio (d/t) < 16, $T_H = 4$ min.
FIG. 7 RTRP System In-Service Test, Option I, Pressurizing Sequence

Common uses:

1. manufacturing tests
2. periodic remove & inspect requalification tests
3. in-service pressure schedule(s) simulation

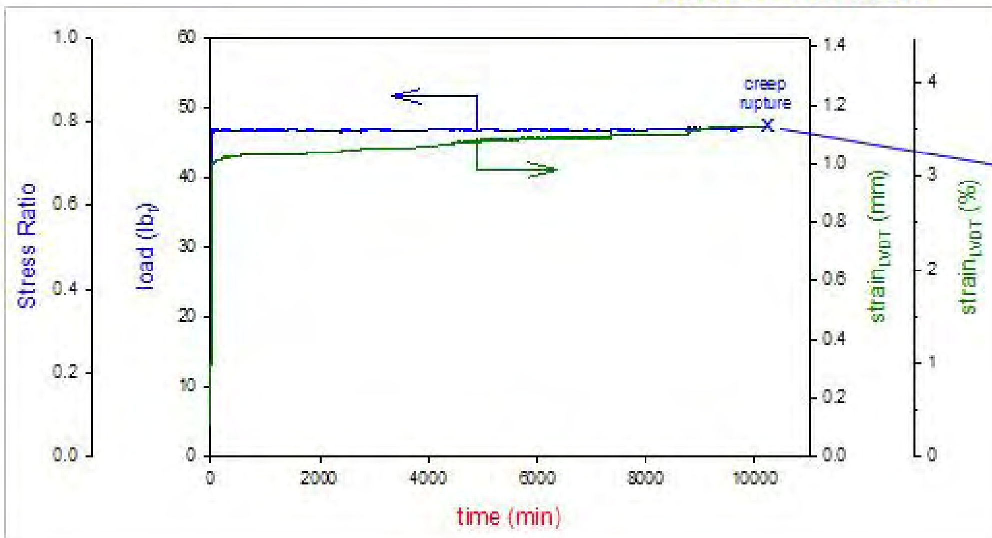
Accelerated Aging Using Stress

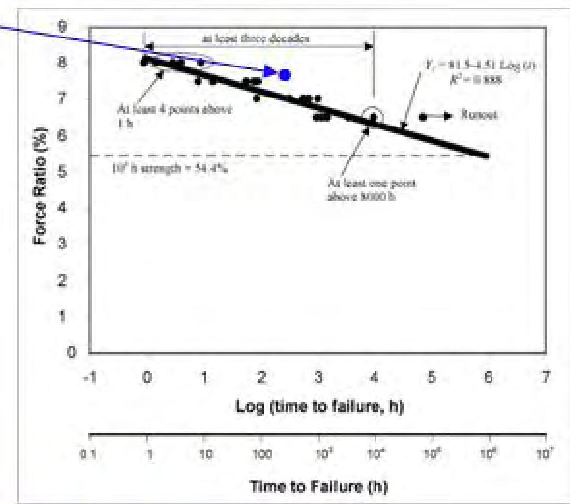
COPVs and Strand

- Commonly used to estimate the creep, i.e., stress rupture lifetime of structural composites at lower load ratios than used in test §

ASTM D7337 Creep Rupture Method

WSTF data on 1140-denier Kevlar® 49/LRF-092 epoxy strand, 32-mm gage length, with poured Epon® 828/diethylenetriamine (DETA) tabs





Objective

Plot stress ratio vs. log time to failure to predict when SR will occur at a given operational stress ratio

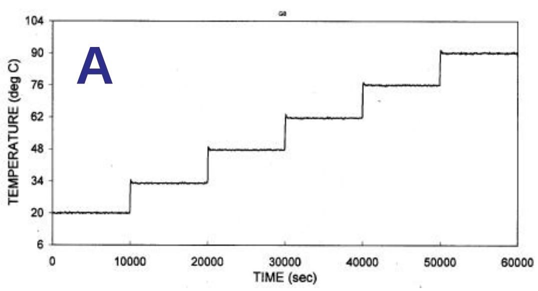
§ ASTM D 7337, *Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars*, American Society for Testing and Materials, West Conshohocken, PA (2007).

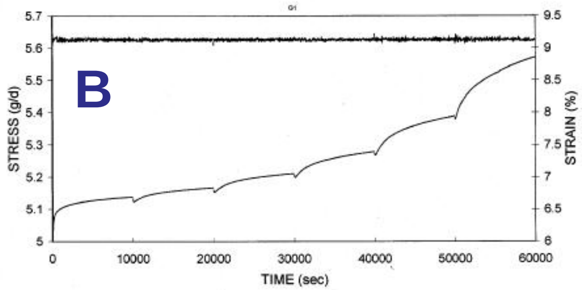
Accelerated Aging Using Temperature

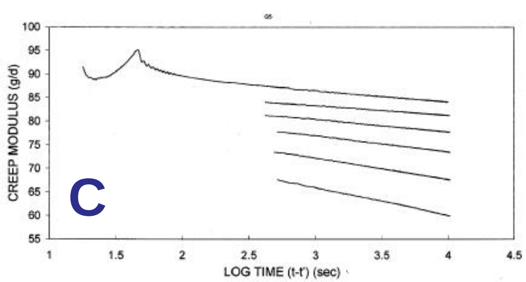
COPVs and Strand

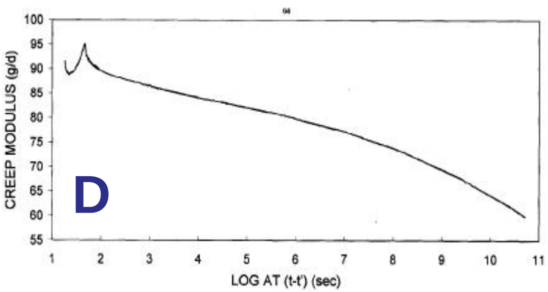
ASTM D 6992 Stress Rupture Method

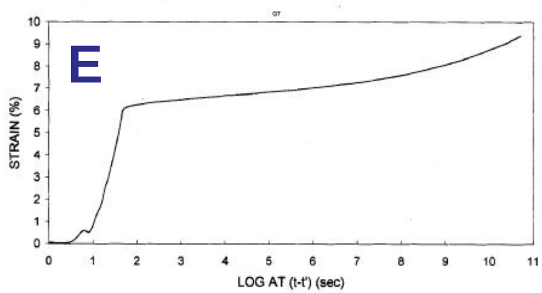
Used during NNWG-sponsored NDE of COPV SR project conducted on 6.3-in-diameter Kevlar®/epoxy and carbon/epoxy COPVs











Procedure

A. Subject strand specimen to stepped isotherms

B. Monitor creep strain at constant stress

C. Convert creep strain to creep modulus and rescale temperature segments to achieve slope matching versus log time

D & E. Correct for thermal expansion and shift data to yield D) creep modulus, and E) creep strain master curves

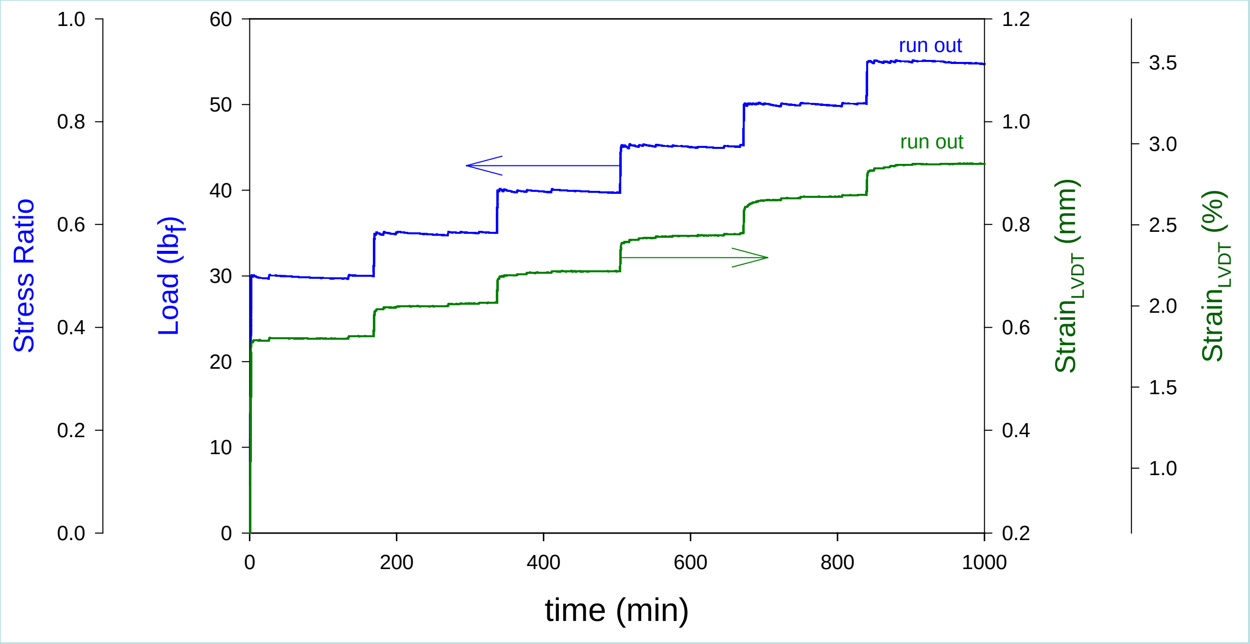
§ ASTM D 6992, *Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method*, American Society for Testing and Materials, West Conshohocken, PA (2008).

Accelerated Aging Using Stress

COPVs and Strand

Stepped Stress Method (SSM) §

1140 denier ATK Kevlar® 49/epoxy strand
32-mm gage length, poured Epon® 828/ tabs



Objective:

Generate strain vs. log time master curve to predict when SR will occur at a given stress level

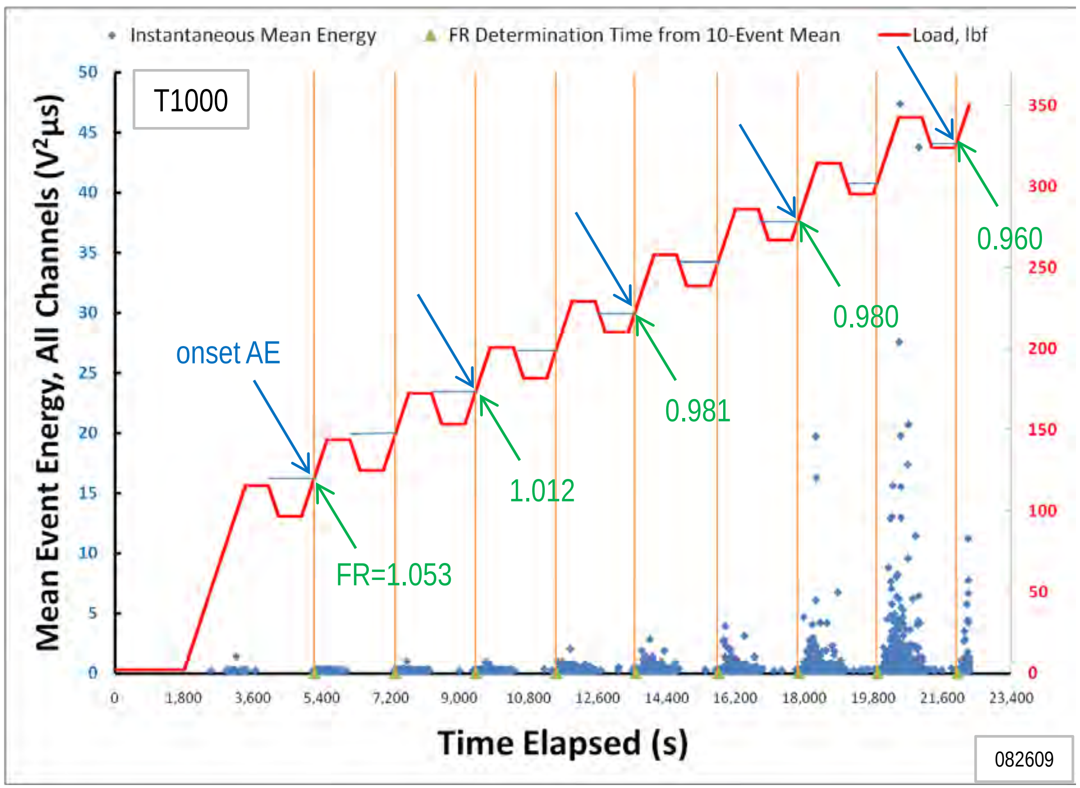
No ASTM or equivalent standard adopted at this point

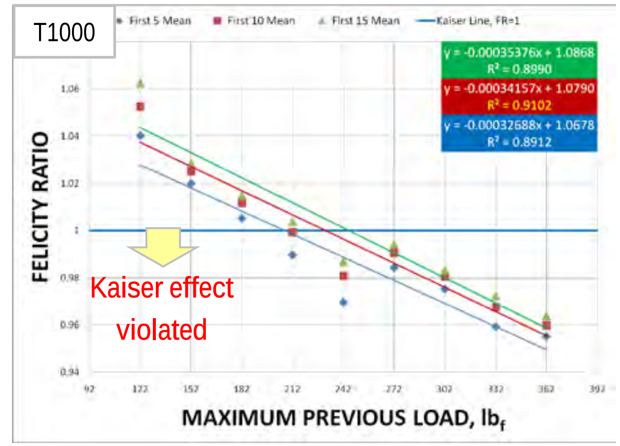
§ Abernethy, Robert B., *The New Weibull Handbook*, Section 6.17, "Accelerated Testing," Fifth Edition, North Palm Beach, FL: Robert B. Abernethy, December 2006.

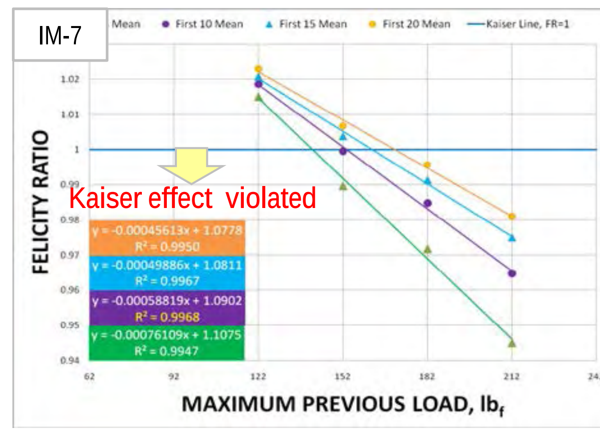
Intermittent Load Hold Testing

COPVs and Strand

- Intermittent load hold (ILH) stress schedules offer a quick way to identify severe accumulated damage using the Felicity ratio:







- ILH profile is based on the pressure tank examination procedure§

ASTM E 1067, *Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels*, American Society for Testing and Materials, West Conshohocken, PA, 19428-2959, 2001.

Proof Cycling Acoustic Emission Test

COPVs (ASME Test)

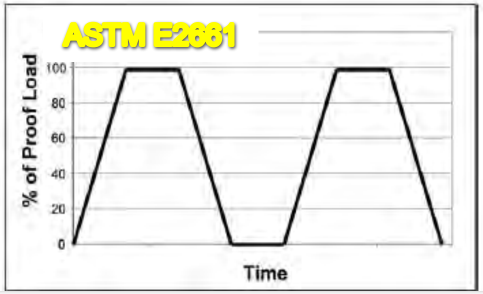
AE event decay rate analysis on load holds using ASME Section X, Appendix 8 §

$$y = Ae^{-Bt} + C$$

Acceptance criteria from ASME Section X Mandatory Appendix 8 and NB10-0601 Supplement 9 :

Acceptable Event Stability:

$-0.1 < B < -0.0001$ & $R^2 \geq 0.80$

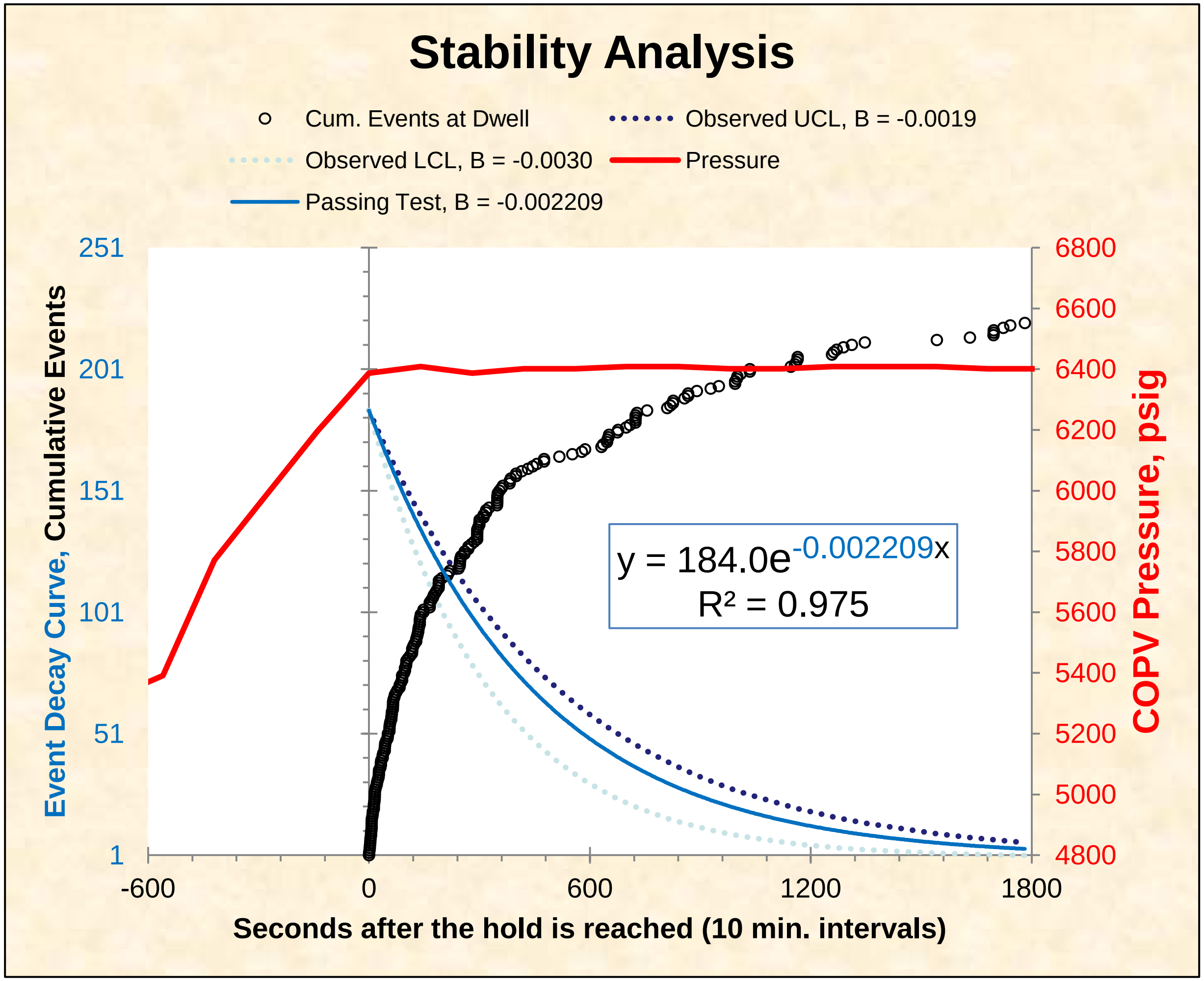


Shape factor B can also be expressed as the time required for the structure to emit 99% of events on a dwell.

$$t_{99\%} = \frac{\ln(0.01)}{B}$$

25 to 40 minutes

(1535 to 2424 sec)



§ *ASME Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels, Section X, Appendix 8-620 Supplementary Examination Requirements, latest revision.*

Composite Conference 2012

Experience Developing ASME Section X Class III Pressure Vessels

Norman L. Newhouse, Ph.D., P.E., Lincoln Composites
Brock Peterson, Lincoln Composites

Development of ASME Section X Class III

- BPV Project Team on Hydrogen Tanks formed in 2004
  - Scope included H2 tanks of all types
  - Worked with Section X on full composite reinforced
- Initially proposed as Code Case, but went directly to Code
  - Approved in 2009
  - Published in 2010 edition of Section X
  - Covered H2 at pressures from 3,000 to 15,000 psi
- Details reported in PVP2010-25349

Manufacturing Facility Approval

- Facility audit performed by the National Board of Boiler and Pressure Vessel Inspectors
- Authorized Inspector is American Bureau of Shipping (ABS), others are available
- Quality manual is required
  - National Board required generation of a quality manual specifically for ASME products
  - Other products (ISO, CSA, ECE, TPED, PED) built in Lincoln facility are satisfied by LC's standard quality manual
- Annual facility audit and 3 year National Board recertification audit required

Manufacturing Facility Approval

- ASME code requirements necessitates many tests and certification of vendors and their processes not normally required by other agencies
- Preferred to have representative production in progress, but an actual ASME Section X tank does not need to be in production

Pressure Vessel Material Requirements

- General materials requirements in construction records:
  - Laminate materials shelf life, storage conditions, and vendor certifications
  - Cure assessment (Barcol hardness or other suitable method)
  - Resin viscosity, specific gravity, gel time and peak exotherm temperatures
  - Resin interlaminar shear strength
- These data points are normally at a qualification level (rather than for each batch), by reference to certifications, or by inference from manufacturing and proof test in many standards and regulations

Pressure Vessel Qualification

- Design qualification tests are similar to most composite pressure vessel design standards

	ASME Section X Class III	CSA, ISO, ECE standards
burst	x	x
ambient cycle	x	x
leak-before-burst	x	x
bonfire		x
penetration	x	x
acid environment	x	x
flaw tolerance	x	x
accelerated stress rupture	x1	x
extreme temperature pressure cycle	x1	x
resin shear strength	x	x
drop		x
boss torque	x	x
permeation	x	x
natural gas cycling		x

x1 – tests are combined in temperature creep test

Pressure Vessel Manufacturing

The manufacturing specification is part of the fabricator's construction records, including:

- Essential variables for liner and bosses/nozzles
  - Dimensions, min thickness, straightness and out-of-round tolerances
  - Process and spec of manufacture
  - Heat-treatment, temps, duration, and tolerances
- Essential variables for laminate materials
  - Laminate construction including the number of strands used, the allowable gap between the bands, the allowable gap within the bands, overlap in the laminate
  - Curing process, temperatures, duration and tolerance
- Essential variables for laminate manufacture
  - Specific wind patterns for fiber strands
  - Filament winding tensioning, winding speed, and bandwidth and spacing

Pressure Vessel Inspection

- Examiner performing visual tests must be qualified with vision tests specific to ASME.
- Visual examination per table 8-600.2.1-1.
- Minimum composite thickness requirement
- Post-hydrotest metallic component liquid penetrant examination
- Acoustic emission examination during proof test

Acoustic Emission Inspection

- Acoustic Emission testing has been used successfully on Section X Class II pressure vessels
- Included in Class III requirements to give added assurance, given higher pressures and lower FS
- Inspection adds 1/2 to 1 hour to manufacturing process
- Approximately 2 months to get report on analysis of vessels
  - Likely to be reduced wait time on future production
  - Few vendors capable of performing analysis
- LC is not aware of any instances in which a production vessel would have failed this test

Pressure Vessel Field Service

- 100+ vessels manufactured in December 2011
- Cleared for service in February 2012
- Service on oil platforms – tensioning system
  - Prior vessels qualified under Section X Class I
- No problems in service

Summary

- ASME Section X Class III Code published in 2010
- Lincoln Composites manufactured first Section X Class III pressure vessels
  - Facility approved per ASME requirements
  - Vessel qualification per Section X Class III requirements
- ASME requirements are rigorous, but achievable
  - Value of acoustic emission testing at time of manufacture is being debated
- Vessels have been placed in service



NIST Overview of Codes and Standards Activities

David McColskey
Material Reliability Division
Boulder, CO

NIST Locations

Gaithersburg, MD
Boulder, CO

U.S. Department of Commerce Boulder Laboratories

U.S. DOC NIST Gaithersburg, MD

NIST's mission:

To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.

NIST's vision:

NIST will be the world's leader in creating critical measurement solutions and promoting equitable standards. Our efforts stimulate innovation, foster industrial competitiveness, and improve the quality of life.

NIST's core competencies:

Measurement science
Rigorous traceability
Development and use of standards

National Institute of Standards and Technology

Material Measurement Laboratory

Material Reliability Division…Boulder, CO

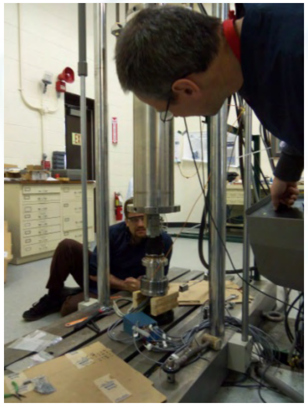
- **Structural Materials Group….**
- Conduct research on properties of materials from nano-size to the largest test specimens in the world
- *Conduct oil, gas and CO2 pipeline research (tensile, fatigue, fracture and corrosion testing)*
- Conduct research on Hydrogen pipeline and storage vessel materials
- Alternative fuel projects (and associated microbiological induced corrosion)
- Fire-resistive steel for high-rise construction research program
- Metals and composites testing in extreme environments

Additionally, MRD has Biological and Biomaterials facilities and Nanomechanics facilities for materials characterization

Structural Materials Group

- **Major Technical Themes**
  - **Fatigue and Fracture**
  - **Structural Reliability**
  - **Non Destructive Evaluation**

- **Major Capabilities and Expertise:**
  - **Mechanical Testing in Extreme Environments**
  - **Finite Element Analysis**
  - **Acoustic Emission**
  - **Welding and Joining**
  - **Metallography/Metallurgical Analysis**
  - **Fracture Mechanics**
  - **Failure Analysis**



NIST and Standards: In the Beginning…..

The **National Bureau of Standards (predecessor to NIST)** was established by Congress in 1901, with a charge to take custody of standards of physical measurements in the US and to solve "problems which arise in connection with standards."

At that time:

- Eight different "authoritative" values for the gallon
- Standards needed for nascent American electrical industry
- American instruments sent abroad for calibration
- Consumer products and construction materials uneven in quality and were unreliable

The need for standards was dramatized in 1904 when 1500 buildings burned down in Baltimore, MD., because of a lack of standard fire-hose couplings. Firefighters arriving from DC, PA, DE, and NY were ineffective in fighting the fires because they couldn't connect to the hydrants or to each others equipment . More than 600 sizes and variations in fire-hose couplings were collected by NBS in a previous investigation. NBS ultimately participated in a national standard for fire-hose connections.

In the early years of the last century, thousands of train derailments were caused by broken rails, broken wheels, flanges, and axles. From 1912 to 1923, NBS subjected failed parts to chemical, microscopic, and mechanical tests and investigated railroad iron and steel constituents and manufacturing. The Bureau reported that the steel industry had not established uniform practices in the manufacture of rails and wheels. By 1930, as better steel went into rails and trains (with NBS's help in standardizing materials and processing). The rate of accidents from these causes fell by two-thirds.

So, What is a Documentary Standard????? (1)

Document, established by **consensus** and approved by a recognized body, that provides for common and repeated use, rules, guideline or characteristics for **activities or their results**, aimed at the achievement of the optimum degree of order in a given context.
Note. Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits. (ISO/IEC Guide 2:1994)

Document, approved by a recognized body, that provides for common and repeated use, rules, guideline or characteristics for **products or related processes and production methods**, with which **compliance is not mandatory**. It may also include or deal exclusively with terminology, symbols, packaging, marking or labeling requirements as they apply to a product, process or production method. (WTO TBT Agreement 1995)

So, What is a Documentary Standard????? (2)

Common and repeated use of rules, conditions, guidelines or characteristics for products or related processes and production methods, and related management systems practices. (NTTAA of 1995 and OMB Circular A-119 of 1998)
http://standards.gov/nttaa.cfm
http://standards.gov/a119.cfm

Market-driven technical specification for a product, service, person, process or system with which compliance is voluntary. (Anonymous)

The U.S. Standardization Model : “One approach among many in the world”

- resembles the nation’s economic structure: Sector-based and driven by market needs
- reflects U.S. culture and traditions
- reflects government/private sector dynamics
- relies strongly on diversity and decentralization

Current Legal and Policy Framework

There is no overarching “standardization law” in the U.S. The legal framework for U.S. Government use and participation is defined in a series of statutes, regulations and administrative orders.

- NTTAA
- OMB A-119
- Trade Agreements Act of 1979
- EOP memo M-12-08, jointly issued by OSTP/OMB-OIRA/USTR (Principles for Federal Engagement in Standards Activities to Address National Priorities)
- Agency specific laws, rule and policies

National Technology Transfer and Advancement Act (NTTAA)

- Directs Federal agencies with respect to their use of private sector standards and conformity assessment practices

- Objective is for Federal agencies to use private sector standards, wherever possible, in lieu of creating government-unique standards.

- Directs NIST to bring together Federal agencies, as well as State and local governments, to achieve greater reliance on voluntary standards and decreased dependence on in-house standards.

OMB Circular A-119 – Policy Guidelines on Implementation of the NTTAA

- Establishes policies on Federal use and development of consensus standards and on conformity assessment activities

- Revised in 1998 to be consistent with, and reinforce, the NTTAA

NIST's Role in Standards

- Provide technical expertise
- Unbiased participant and trusted resource
- Policy/Coordination role
- Leadership role in national priority areas
- Advocate for the U.S. System

NIST Helps to Ensure the Technical Efficacy of Documentary Standards

- By participating as technical experts in the development of test methods; product, system, and process specifications; etc.

- By participating in round robins to collect data to support the development of test methods
  - NIST conducted tests for the tests for elevator fire safety which ASME used in elevator and escalator safety codes
  - Following the collapse of the WTC buildings, NIST proposed a new ASTM standard for fire-resistant steel and conducted extensive testing for its use in high-rise construction

- By providing Standard Reference Data, Calibrations Tests and Standard Reference Materials needed to calibrate instruments used in test methods
  - There are currently ~800 NIST Standard Reference Materials listed within ASTM, and ~1300 total products,

NIST Participation in Documentary Standards

Approximately 400 staff members (about 1/3 of technical staff) participate in about 1300 committees in 120 voluntary standards organizations

- Organizations include international standards organizations, SDO’s domiciled in the U.S. and consortia

Focus is on analytical testing, building and construction, health care, information technology, manufacturing, telecommunications, infrastructure, energy, interoperability

2010/2011 NIST Committee Membership in SDO's

ASTM (327)	ASME (43)
ISO (92)	SEMI (39)
IEEE (80)	IETF (30)
INCITS (75)	CIE (13)
ASHRAE (48)	NFPA (21)
IEC (45)	ACI and ASA (18 each)

Plus many other SDO memberships

Special thanks to the Standards Coordination Office/ADLP/NIST for their assistance and provision of many of the presented slides.

For more information on the government role in standards:
http://www.standards.gov

Thank you

Status of ESA Composite Pressure Vessel Codes and Standards

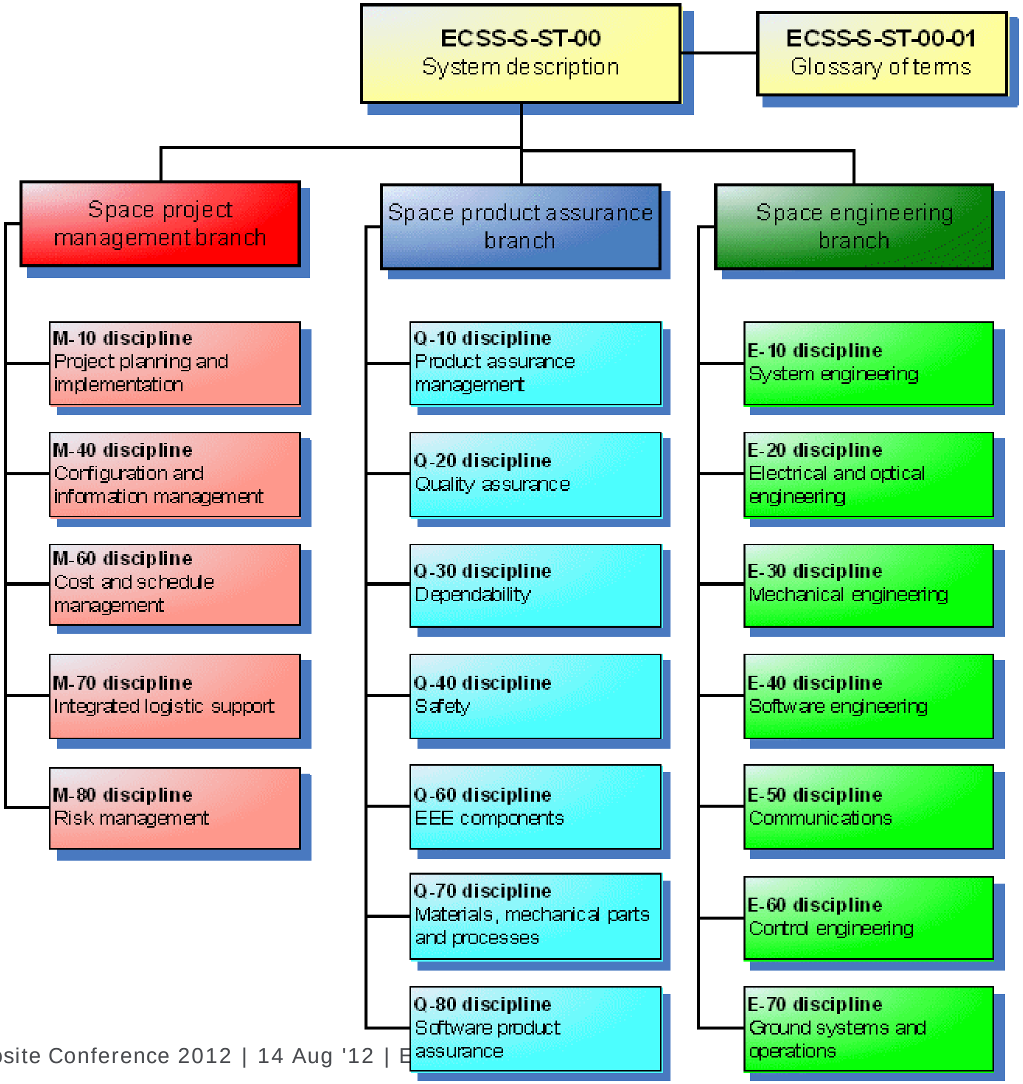
Gerben Sinnema
Composite Conference 2012
14 Aug '12

Introduction

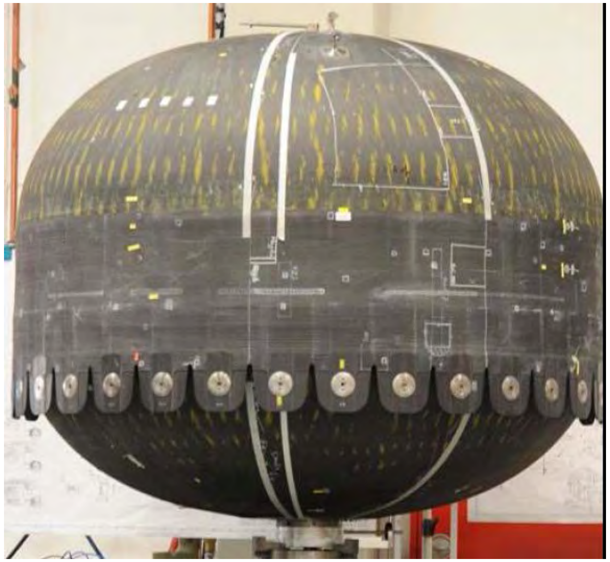
- The ECSS standard for pressurized hardware, ECSS-E-ST-32-02C 'Structural design and verification of pressurized hardware', was released in 2008, and presented during a COPV workshop in Rome in October 2008.
  (see also http://www.congrex.nl/08a11/copv_programme.asp)
- In November 2008 the standard was updated to rev.1 in order to harmonize MDP and MEOP definitions between ECSS standards.
- This presentation will highlight significant developments for composite (overwrapped) pressure vessels and pressurized structures, that may affect the next issue of the standard.

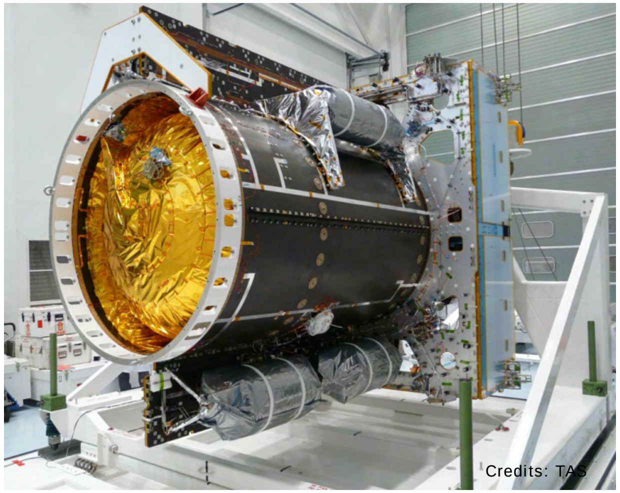
ECSS

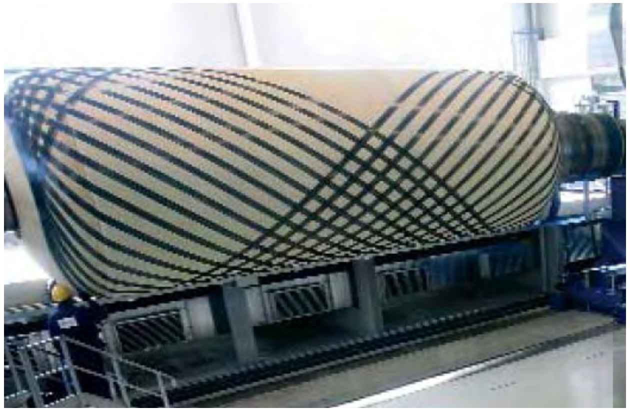
- The European Cooperation for Space Standardization (ECSS) is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities.
- Members:
  - European Space Agency (ESA)
  - National Space Agencies
  - Eurospace (industry)



Applications - Examples





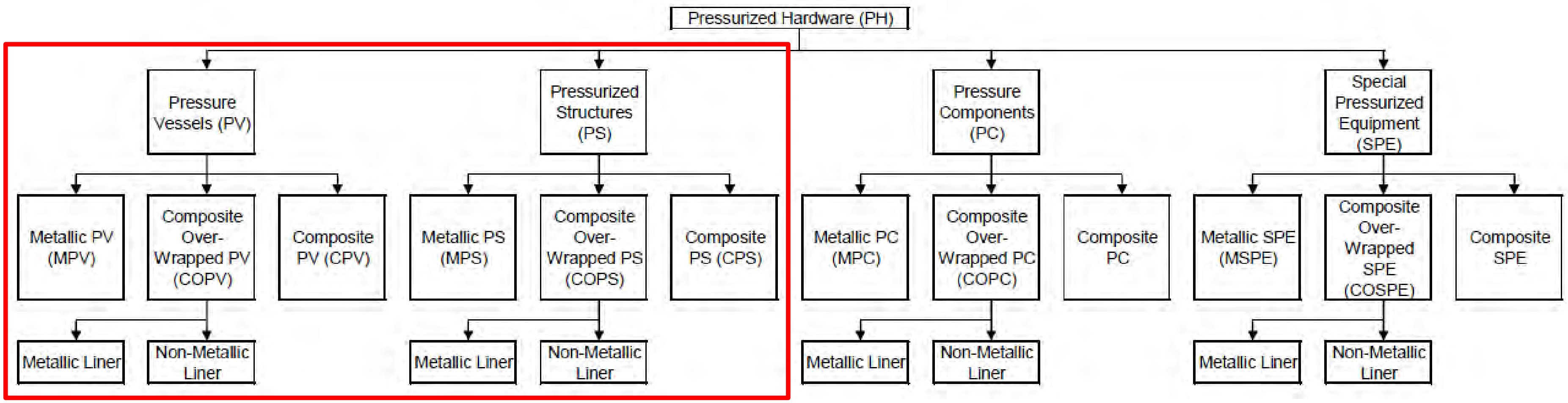


Pressurized Hardware standards

- MIL-STD-1522A “Standard General Requirements For Safe Design And Operation Of Pressurized Missile And Space Systems”
    - Extensively used until recently, but now obsolete
- ANSI/AIAA S-080-1998 “Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components” &
  ANSI/AIAA S-081A-2006 “Space Systems - Composite Overwrapped Pressure Vessels (COPVs)”
    - Replacement of MIL-STD-1522A
    - Introduction of specific requirements for COPVs
- ISO 14623 “Space systems - Pressure vessels and pressurized structures - Design and operation”
    - Similar to AIAA standards

→ **Until ECSS-E-ST-32-02C No European Standard Existed!**

Pressurized hardware types covered by ECSS-E-ST-32-02C:



MDP and MEOP definitions – Rev. 1

- ECSS-E-ST-32-02C uses MDP as baseline, not MEOP. It was decided to harmonize MDP and MEOP definition over various standards in the higher level standard ECSS-E-ST-32C 'Structural general requirements' (rev.1, Nov. 2008)
- <u>maximum design pressure (MDP)</u>: pressure equal to MEOP*K_m*K_p
  - NOTE 1 MDP correspond to design limit loads
  - NOTE 2 MDP is equal or larger than MEOP.
  - NOTE 3 K_m is a factor which takes into account the representativity of the mathematical models predicting MEOP and it is defined by the entity defining MEOP (for definition of K_m see ECSS-E-ST-32-10 'Factors of safety').
  - NOTE 4 K_p is the project factor (for definition of K_p see ECSS-E-ST-32-10 'Factors of safety')

MDP and MEOP definitions – Rev. 1

- maximum expected operating pressure (MEOP): highest pressure that a system or component is expected to experience during its mission life in association with its applicable environment
  - NOTE 1 For mission life see definition in 3.2.29 (of the standard).
  - NOTE 2 MEOP corresponds to limit loads.
  - NOTE 3 MEOP includes effects of temperature and acceleration on pressure, maximum relief pressure, maximum regulator pressure and effects of failures within the system or its components. The effect of pressure transient is assessed for each component of the system and used to define its MEOP.
  - NOTE 4 MEOP includes effects of failures of an external system (e.g. spacecraft), as specified by the customer, on systems (e.g. propulsion) or components.
  - NOTE 5 MEOP does not include testing factors, which are included in ECSS-E-ST-32-02 'Structural design and verification of pressurized hardware' and ECSS-E-ST-10-03 'Testing'.

Minimum Factors of Safety

- Minimum Factors of Safety for pressure vessels:

Load	FOSY	Proof factor	FOSU	Burst Factor
Internal pressure	1,0	1,25	1,0	1,5
Mechanical loads (including external pressure)	Values specified in ECSS-E-ST-32-10			

- NOTE: ECSS-E-ST-32-10C ‘Factors of safety’.

Minimum Factors of Safety

- Minimum Factors of Safety for pressurized structures:

Table 4-2: Factors of safety for PS (unmanned mission)

Load	FOSY	Proof factor	FOSU	Burst Factor
Internal pressure	1,1	1,1	1,25	1,25
Mechanical loads (including external pressure)	Values specified in ECSS-E-ST-32-10			

Table 4-3: Factors of safety for PS (manned mission)

Load	FOSY	Proof factor	FOSU	Burst factor
Internal pressure	1,1	1,1	1,4	1,4
Mechanical loads (including external pressure)	Values specified in ECSS-E-ST-32-10			

Table 4-4: Factors of safety for manned modules

Load	FOSY	Proof factor	FOSU	Burst factor
Internal pressure	1,65	1,5	2,0	2,0
Mechanical loads (including external pressure)	Values specified in ECSS-E-ST-32-10			

LBB Failure Mode Demonstration by analysis

Per ECSS-E-ST-32-02C:

- It shall be shown that, at MDP, an initial surface crack with a flaw shape (a/c), ranging from 0.2 to 1.0, meets the following conditions:
  - it does not fail as a surface crack; and
  - it grows through the wall of the hardware to become a through crack with a length greater than or equal to <u>10 times the wall thickness</u> of the metallic item and remains stable.
- When LBB demonstration is based on a through crack with a length less than 10 times the wall thickness (...) , the considered initial crack size shall be justified.

LBB Failure Mode Demonstration by test using coupons

Per ECSS-E-ST-32-02C:

- The flaws shall be surface cracks and the flaw shape of the pre-fabricated surface cracks shall range from a/c = 0.2 to 1.0.
- The initial surface crack size shall be justified.
- Stress (or strain) cycles shall be applied to the specimens with the maxi mum stress (or strain) corresponding to the MDP level and minimum stress (or strain) kept to zero, or actual minimum stress (or strain), until the surface crack grows through the specimen's thickness to become a through crack.
- It shall be shown that the length of the through crack becomes equal to or greater than <u>10 times the specimen's thickness</u> and remains stable at MDP.

LBB Failure Mode Demonstration by test using full-scale article

Per ECSS-E-ST-32-02C:

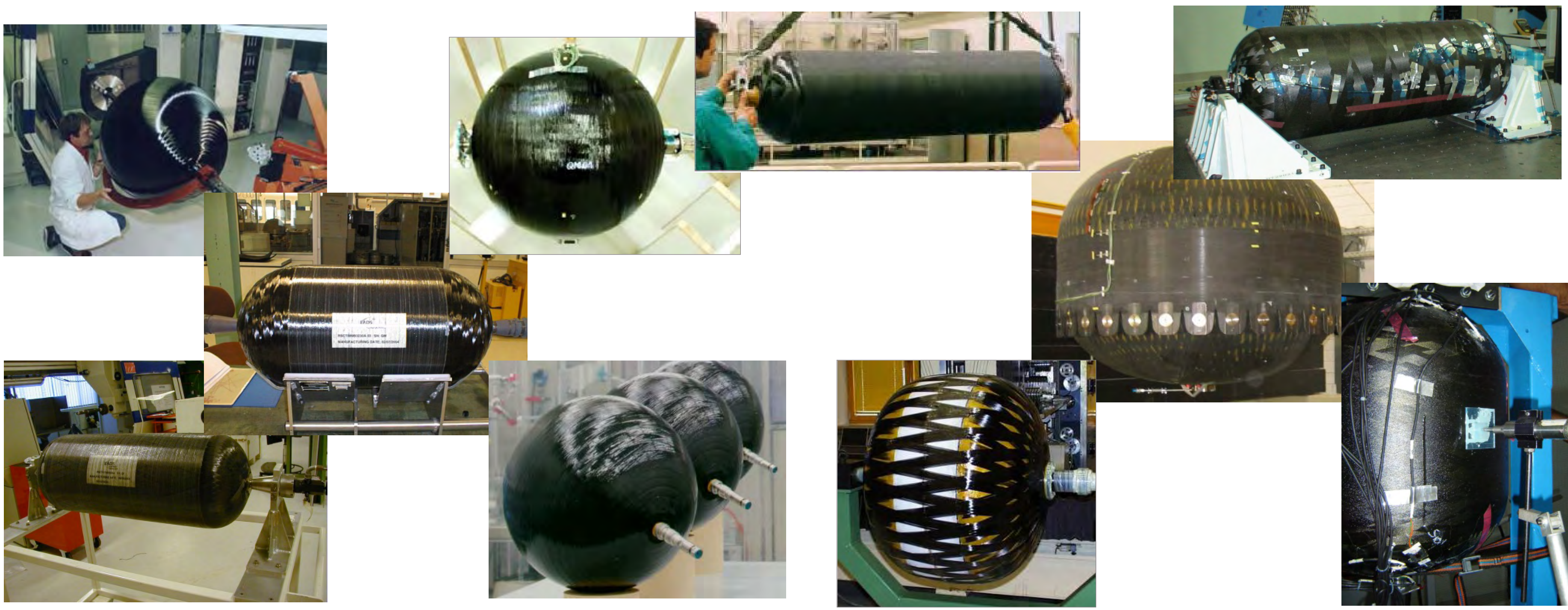
- The type and initial size of pre-fabricated flaws shall be justified.
- For pre-flawed metallic items, the flaws shall be surface cracks and the aspect ration of the pre-fabricated surface cracks shall range from a/c = 0.2 to 1.0.
- Location and orientation of pre-fabricated flaws shall be the most critical with regard to LBB response.
- Pressure cycles shall be applied to the pressurized hardware, with the upper press ure equal to MDP and the lower pressure greater than or equal to zero.
- After a flaw has grown through the thickness to become a through flaw and leakag e has been detected, internal pressure shall be increased up to MDP.
- (...) After above has been met, no burst occurs at MDP and leak rate is equal to or greater than a value defined with customer approval (...).
- The full-scale test shall duplicate the loading and pressurization medium (gas or liquid) of the flight hardware.

Potential subjects for the next update of ECSS-E-ST-32-02

- More detailed damage control requirements?
- More detailed stress rupture requirements?
- More emphasis on COPV liner LBB verification by means of (similarity with) full-scale tests? (with ref. to e.g. 'USAF interim letters' and AFSPCMAN 91-710)
- Revisit safe life requirement for safe life verification of COPV liners where the primary concern is reliability? (i.e. NHLBB failure mode) Implementation of adequate NDI remains a challenge as liner thickness decreases.

ECSS Task Force “Damage Control of COPVs” 2007-2008

- Review of European COPVs (Astrium, MT-Aerospace, Thales-Alenia Space), and overseas practices.
- Detailed damage control requirements were not implemented in ECSS-E-ST-32-02C.



Developments in damage control practice

- Risk for safety recognized.
  → Covered as needed by flight, launch and/or range safety authorities (e.g. per ISS requirements, AFSPCMAN 91-710)
- Protection for COPV (and composite structural elements more in general) is subsequently increasingly implemented.
- A damage protection system was developed for filament wound SRM of the Vega launcher.
  (See http://www.congrex.nl/10M68/ 'Programme', author Mataloni)

  Note: Proprietary European launcher standards have been harmonized with ECSS.


Credits: ESA

Developments related to stress rupture concerns

- Some high level, qualitative requirements exist.
- ESA is studying the latest developments in stress rupture modeling, and their potential impact on various mission types.
  No clear consensus appears to be reached.
- For manned applications, restrictions emerge on carbon COPV with burst factor <3 and operational stress ratio >50% (ref. e.g. SSP 52005E, recently Issued in March 2012)
- Restrict the proof test level to e.g. 1.25?
- What is sufficiently mature for the next issue of ECSS-E-ST-32-02, especially for unmanned applications?

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

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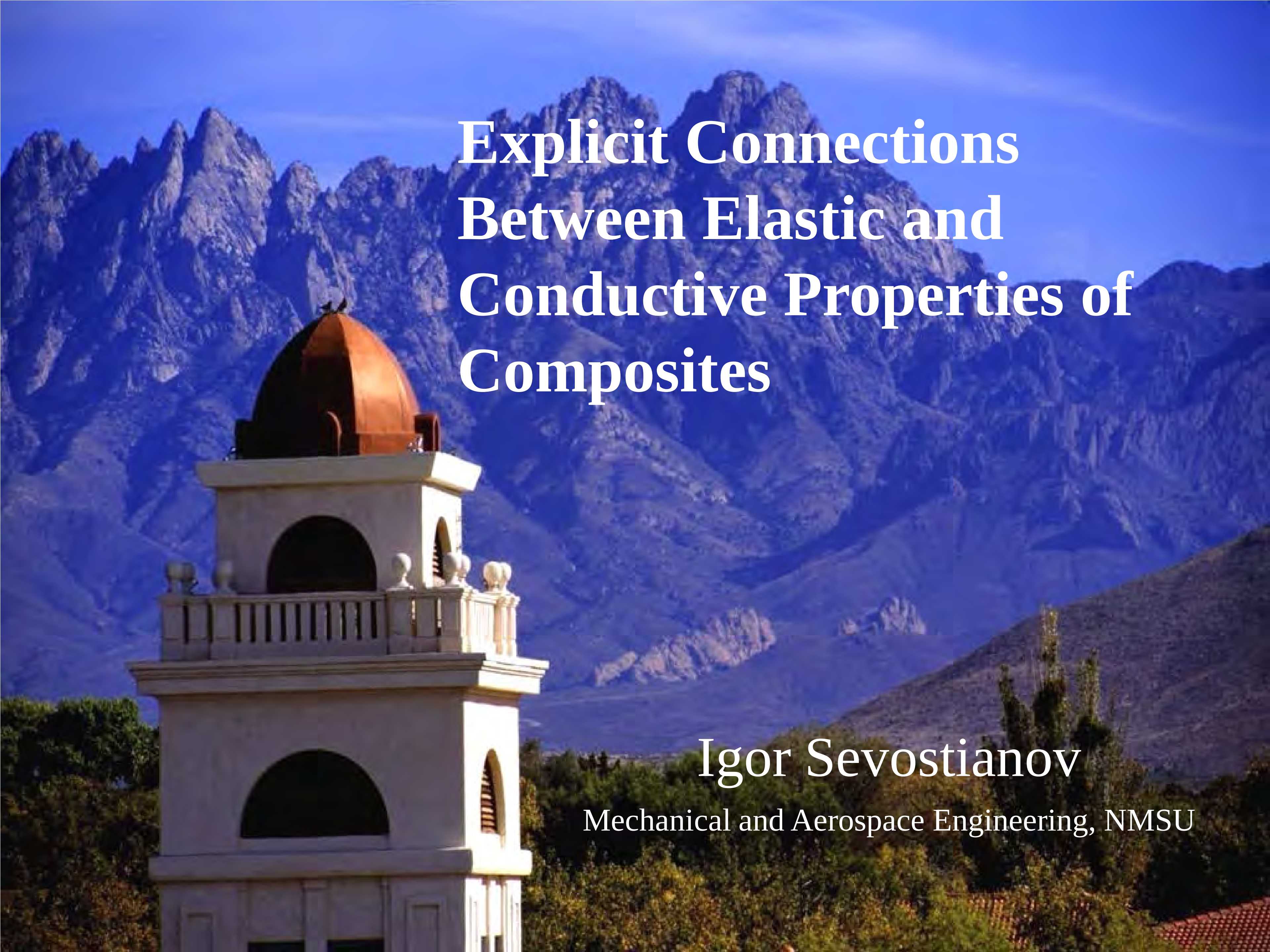
References and Links

- ECSS-E-ST-32-02C 'Structural design and verification of pressurized hardware' (rev.1, 2008)
- MIL-STD-1522A “Standard General Requirements For Safe Design And Operation Of Pressurized Missile And Space Systems” (1986)
- ANSI/AIAA S-080-1998 “Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components”
- ANSI/AIAA S-081A-2006 “Space Systems - Composite Overwrapped Pressure Vessels (COPVs)”
- ISO 14623 “Space systems - Pressure vessels and pressurized structures - Design and operation” (2003)
- ECSS-E-ST-32C ‘Structural general requirements’ (rev.1, 2008)
- ECSS-E-ST-32-10C ‘Factors of safety’ (rev.1, 2009)
- ECSS-E-ST-10-03C ‘Testing’ (2012)

References and Links

- AFSPCMAN 91-710 ‘Range Safety User Requirements Manual’ (2004)
- 'Interim Safety Requirements for Design, Test, and Ground Processing of Flight Gr/EP COPVs ...', USAF, 23 Nov 1993;
- 'Interpretations of the Design, Test, and Ground Processing of Flight Gr/EP COPVs', USAF, 25 Apr 1994
- SSP 52005E ‘Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures - International Space Station Program’ (2012)
- For access to ECSS standards: www.ecss.nl (requires registration)
  Or contact the author.
- Fracture Control Workshop/TIM:
  2009: http://www.congrex.nl/09c11/programme.asp
  2011: http://www.congrex.nl/10M68/ ‘Programme’
- COPV Workshop 2008:
  http://www.congrex.nl/08a11/copv_programme.asp



Explicit Connections Between Elastic and Conductive Properties of Composites

Igor Sevostianov

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A fundamental and practical question:

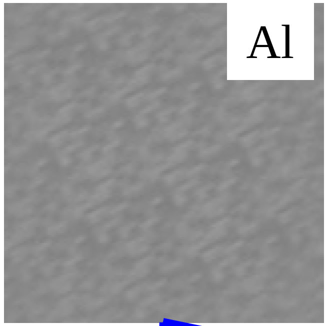
Can different effective physical properties of anisotropic materials be explicitly linked to one another?

(For example, elasticity-conductivity)

Such cross-property connections are especially useful if one property (say, electric conductivity) is easier to measure than another one (anisotropic elastic constants)

We consider materials that can be described as ***matrices containing multiple isolated inhomogeneities*** of diverse shapes and orientations (cracks, pores, foreign particles).

Cross-property connections



E =70GPa

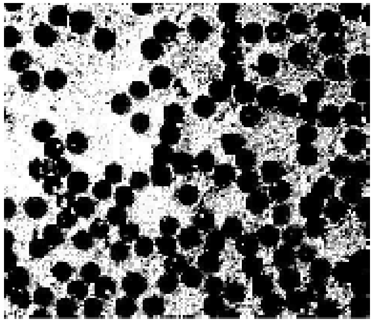
ν = 0.33

K_T =146 W/(mK)

R_e =2.65x10^{-8}-m

Changes in all the material properties due to the microstructure

(1)



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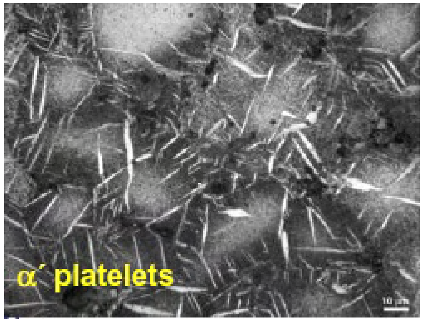

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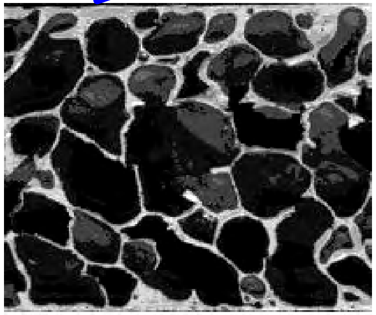


(1)Aluminum alloy reinforced with boron particles; (2) Radiation damage in aluminum alloy; (3)Aluminum foam

Bristow's (1961) elasticity-conductivity connection for a microcracked material

$$\frac{E_0 - E}{E} = \frac{16}{45}\frac{\left(1-\nu_0^2\right)\left(10-3\nu_0\right)}{2-\nu_0}\rho$$

$$\frac{K_0 - K}{K} = \frac{16}{9}\frac{1-\nu_0^2}{1-2\nu_0}\rho$$

$$\frac{G_0 - G}{G} = \frac{32}{45}\frac{\left(1-\nu_0\right)\left(5-\nu_0\right)}{2-\nu_0}\rho$$

$$\rho = \left(1/V\right)\sum a_i^{\,3}$$

$$\frac{k_0 - k}{k} = \frac{8}{9}\rho$$

Observing that changes in both the elastic and the conductive properties are expressed in terms of the same crack density parameter and eliminating it

$$\frac{E_0 - E}{E} = \frac{2\left(1-\nu_0^2\right)\left(10-3\nu_0\right)}{5\left(2-\nu_0\right)} \frac{k_0 - k}{k}$$

$$\frac{K_0 - K}{K} = \frac{2\left(1-\nu_0^2\right)}{1-2\nu_0} \frac{k_0 - k}{k}$$

$$\frac{G_0 - G}{G} = \frac{4\left(1-\nu_0\right)\left(5-\nu_0\right)}{5\left(2-\nu_0\right)} \frac{k_0 - k}{k}$$

Cross-property bounds

Cross-property bounds interrelate, in the form of inequalities, the effective elastic and the effective conductive properties. They are universal, in the sense that they hold for all microgeometries.

Milton's (1984) inequality is based on the minimum potential energy principle

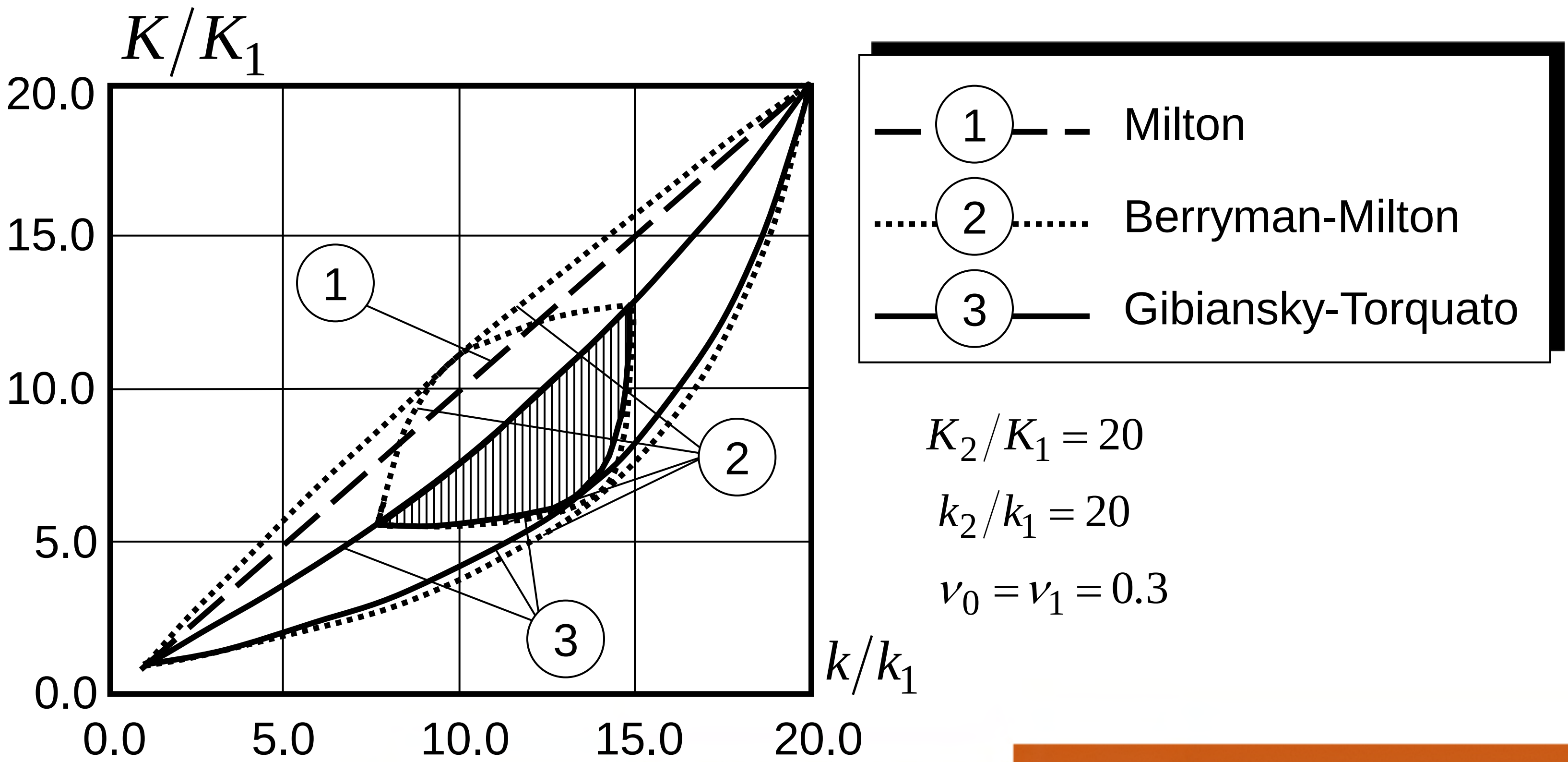
$$\frac{K}{K_1} \leq \frac{k}{k_1}$$

Berryman-Milton's bounds

$$\frac{1}{2}\frac{c_0 k}{c_1 k_1 - k} \leq 21\left(\frac{1+B_0}{5-21B_0}\right) - \frac{21A_0}{5-21B_0}\frac{6c_1 G/G_0}{c_0 - G/G_0}$$

$$A_0 = \frac{6(K_0 + 2G_0)^2}{(3K_0 + G_0)^2} \qquad B_0 = \frac{5G_0(4K_0 + 3G_0)}{(3K_0 + G_0)^2}$$

Gibiansky-Torquato's translation-based cross-property bounds



$K_2/K_1 = 20$

$k_2/k_1 = 20$

$\nu_0 = \nu_1 = 0.3$

Practical needs of materials science call for the cross-property connections that, preferably

- have the **explicit** form;

- can be applied to **strongly anisotropic** microstructures (such as coatings, reinforced plastics, etc);

- remain accurate at **high contrast between the phases** (materials with pores, microcracks or, conversely, hard particles).

Present analysis: Closed form connections for the full set of anisotropic constants

Based on key observation: ***Effects of inhomogeneities on elasticity and conductivity are largely similar***

However: these effects are not fully identical. The (average) *shape* of defects affects these two properties somewhat differently

---

Therefore: Cross-property connections contain shape factor as a parameter. But the shape sensitivity is mild, particularly for pores, and vanishes for strongly oblate shapes

Cross-property connections are implied by proper microstructural parameters

- Cross-property connections – when they are possible – interrelate changes in different physical properties (say, elastic and conductive ones) due to the presence of inhomogeneities.

- Proper microstructural parameters are generally different for different physical properties. The differences can be essential and a connection cannot, generally, be established between the two properties.

- For the *elastic and conductive* properties, the proper parameters are either identical or similar. This leads to explicit cross-property connections obtained by eliminating the mentioned parameters.

Assumptions

- Non-Interaction approximation
- Ellipsoidal shapes

However: Experimental verification of derived connections on

- short fiber reinforced plastics
- metal foams
- plasma-sprayed ceramic coatings

shows Cross-property connections ***continue to hold*** at high concentration of inhomogeneities and for "irregular" shapes

Likely reason: interactions and shape "irregularities" affect elasticity/conductivity in a similar way

Effective elastic properties

For volume V containing ***one*** inclusion, strain per V under applied stress $\boldsymbol{\sigma}$ is a sum

$$\boldsymbol{\varepsilon}_{ij} = \boldsymbol{S}^{0}_{ijkl}\boldsymbol{\sigma}_{kl} + \Delta\boldsymbol{\varepsilon}_{ij}$$

$\boldsymbol{S}_0$ - compliance tensor of the matrix

Due to linear elasticity

$$\Delta\boldsymbol{\varepsilon}_{ij} = \boldsymbol{H}_{ijkl}\boldsymbol{\sigma}_{kl}$$

H - ***compliance contribution tensor of an inclusion***.

Many inhomogeneities

$\Delta\boldsymbol{\varepsilon}^{(k)}$ are linear functions of applied stress:

$$\Delta\varepsilon_{ij}^{(m)} = H_{ijkl}^{(m)}\sigma_{kl}$$

in non-interaction approximation, taken as <u>isolated</u> ones

Effective compliances S_{ijkl} are given by

$$\varepsilon_{ij} = S_{ijkl}^{0}\sigma_{kl} + \sum_{k}\Delta\boldsymbol{\varepsilon}^{(k)} = \left[S_{ijkl}^{0} + \sum_{k}H_{ijkl}\right]\sigma_{kl} \equiv S_{ijkl}\sigma_{kl}$$

Key finding:

Compliance contribution tensor ***H*** can be represented, with good accuracy, in terms of a certain symmetric ***second rank tensor***.

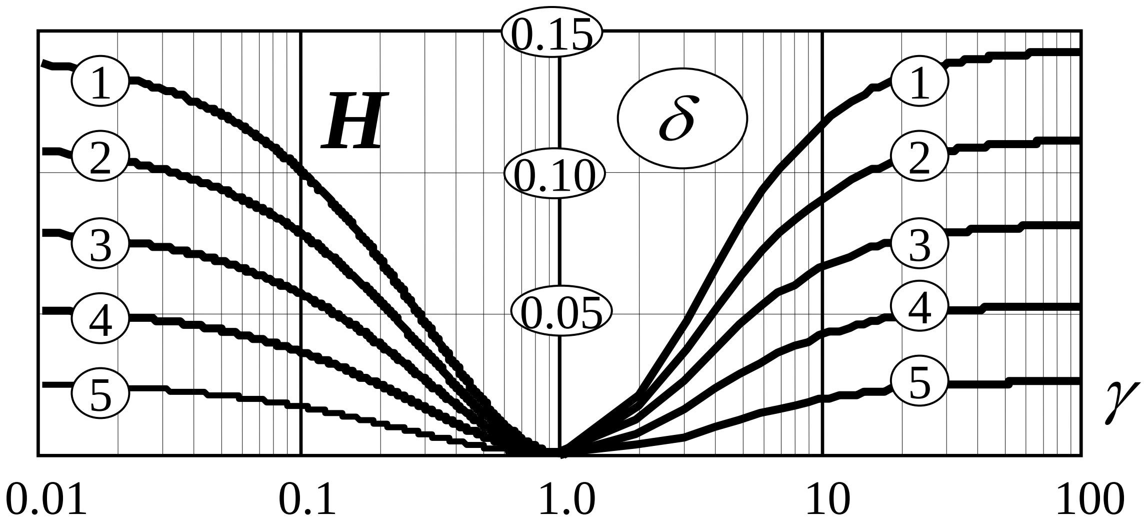
In particular, for a spheroidal inclusion

$$\boldsymbol{H} = \frac{1}{E_0}\frac{V_{cav}}{V}\left[B_1\,\boldsymbol{II} + B_2\boldsymbol{J} + B_3\left(\boldsymbol{nn}\cdot\boldsymbol{J} + \boldsymbol{J}\cdot\boldsymbol{nn}\right) + B_4\left(\boldsymbol{nnI} + \boldsymbol{Inn}\right) + B_5\boldsymbol{nnnn}\right]$$

$$\Big\Downarrow \text{ approximation}$$

$$\boldsymbol{H} = \frac{1}{E_0}\frac{V_{cav}}{V}\left[B_1^*\boldsymbol{II} + B_2^*\boldsymbol{J} + B_3^*\left(\boldsymbol{nn}\cdot\boldsymbol{J} + \boldsymbol{J}\cdot\boldsymbol{nn}\right) + B_4^*\left(\boldsymbol{nnI} + \boldsymbol{Inn}\right)\right]$$

The accuracy of this approximation depends on the inclusion shapes and on contrast in the matrix/inclusions elastic properties



crack → sphere → needle

1. $\nu_0 = 0.1$
2. $\nu_0 = 0.2$
3. $\nu_0 = 0.3$
4. $\nu_0 = 0.4$
5. $\nu_0 = 0.5$

(δ measures maximal, with respect to all stress states, error in elastic potential Δf)

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For a solid with many inclusions

$$\Delta f = (1/2)\,\boldsymbol{\sigma}\boldsymbol{:}\sum \boldsymbol{H}^{(k)}\boldsymbol{:}\boldsymbol{\sigma}$$

And the finding above leads to the possibility to approximate the sum $\Sigma\, \boldsymbol{H}^{(k)}$ by expression that involves a certain *second* rank symmetric tensor $\boldsymbol{\omega}$:

$$\sum \boldsymbol{H}^{(k)} = \frac{1}{E_0}\Big[pb_1\,\boldsymbol{II} + pb_2\boldsymbol{J} + b_3(\boldsymbol{\omega}\cdot\boldsymbol{J} + \boldsymbol{J}\cdot\boldsymbol{\omega}) + b_4(\boldsymbol{\omega}\boldsymbol{I} + \boldsymbol{I}\boldsymbol{\omega})\Big]$$

Conductivity (thermal or electrical)

Assuming a linear conduction law (linear relation between the far-field temperature gradient $\boldsymbol{G}$ and the heat flux vector $\boldsymbol{U}$ per volume V), the *change* due to the inclusion

$$\Delta \boldsymbol{G} = \frac{1}{V} \boldsymbol{H}^{R} \cdot \boldsymbol{U}$$

where symmetric second rank tensor $\boldsymbol{H}^{R}$ can be called the **resistivity contribution tensor of an inclusion.**

Conductivity-elasticity connection for general case of inclusions (approximate):

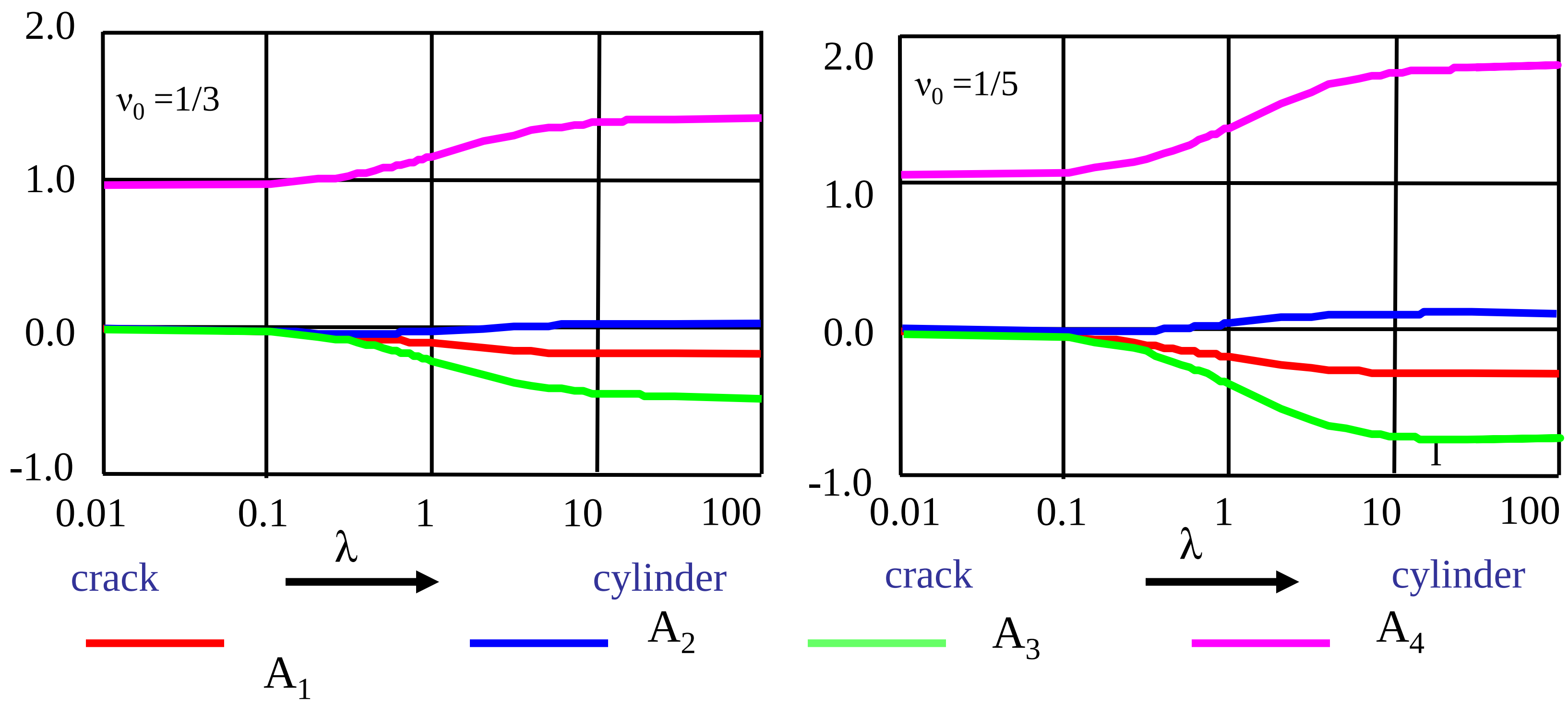
If inclusions' aspect ratios are not correlated with either orientations of the inclusions or their volumes (note that volumes and orientations *may* be correlated)

$$E_0\left(\boldsymbol{S}-\boldsymbol{S}^{\boldsymbol{0}}\right)=\left[A_{\boldsymbol{1}}\boldsymbol{II}+A_2\boldsymbol{J}\right]\left[tr\left(\boldsymbol{K}/k_0\right)-3\right]$$

$$+A_3\left[\left(\boldsymbol{K}/k_0-\boldsymbol{I}\right)\boldsymbol{I}+\boldsymbol{I}\left(\boldsymbol{K}/k_0-\boldsymbol{I}\right)\right]+A_4\left[\left(\boldsymbol{K}/k_0-\boldsymbol{I}\right)\cdot\boldsymbol{J}+\boldsymbol{J}\cdot\left(\boldsymbol{K}/k_0-\boldsymbol{I}\right)\right]$$

Factors $A_{1\text{-}4}$ are aspect ratio-dependent, reflecting the fact that shapes affect elasticity/conductivity somewhat differently

Shape sensitivity is relatively mild



Implication: only approximate knowledge of average shapes is needed

Cross-property connections in simplest cases

Microcracked anisotropic material

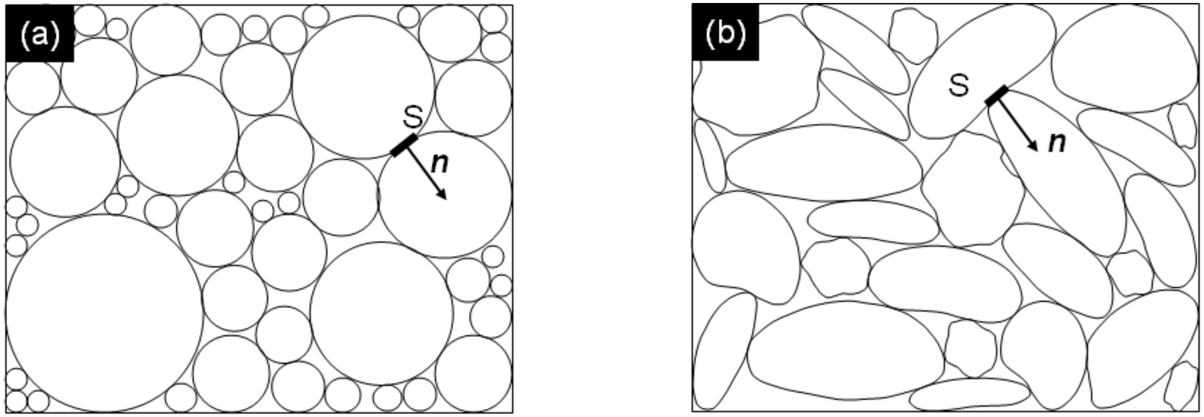
$$\frac{E_0 - E_i}{E_i} = \frac{4\left(1-\nu_0^2\right)}{2-\nu_0}\frac{k_0 - k_i}{k_i}$$

Young's modulus *vs.* conductivity in any direction x_i

Material with spherical voids

$$\frac{E_0 - E_{eff}}{E_{eff}} = \frac{\left(1-\nu_0\right)\left(9+5\nu_0\right)}{\left(7-5\nu_0\right)}\frac{k_0 - k_{eff}}{k_{eff}}$$

Similar cross-property connection holds for a granular material



Both conductivity and elasticity of Hertzian contacts depend on square roots of contact areas, leading to

$$\frac{E_0 - E_i^{eff}}{E_i^{eff}} = 2\left(1 - \upsilon_0^2\right)\frac{k_0 - k_i^{eff}}{k_i^{eff}}$$

Inhomogeneities of irregular (non-ellipsoidal) shapes

Analyses of relative importance of various “irregularity factors”: this difficult, and largely incomplete, task needs both the theoretical guidance and numerical studies.

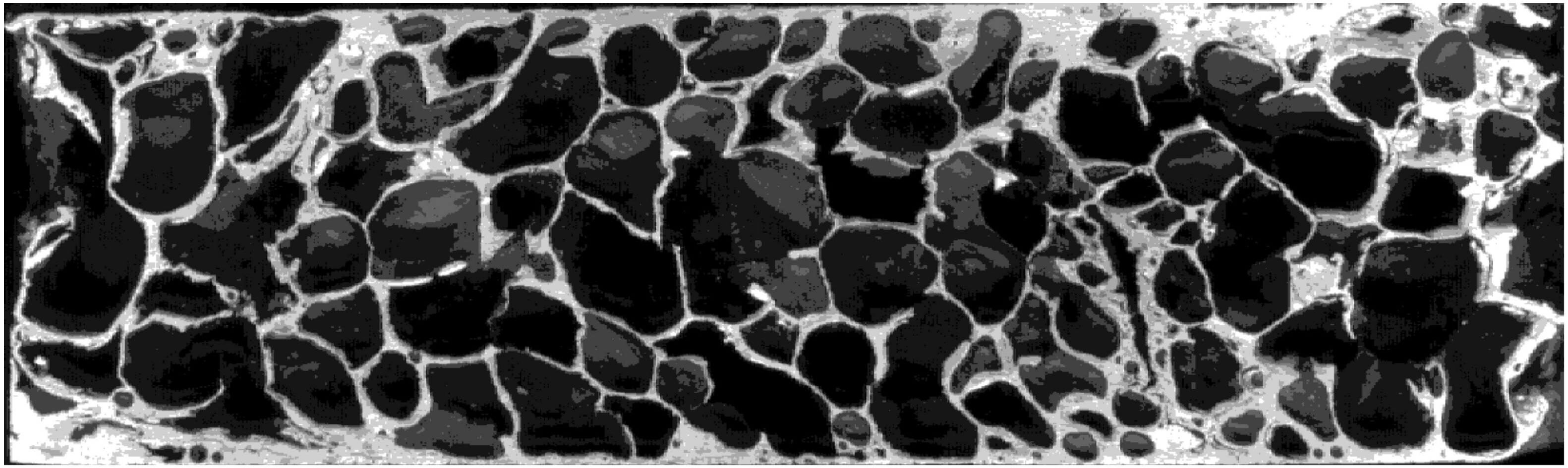
Hypothesis: “irregularity factors” affect elasticity/conductivity in similar way

Experimental verification of cross-property connections

- Aluminum foam
- Short fiber reinforced composite
- Plasma sprayed ceramic coating
- Composites with microcracks and micropores
- Metal with microcracks (due to cycling loading)

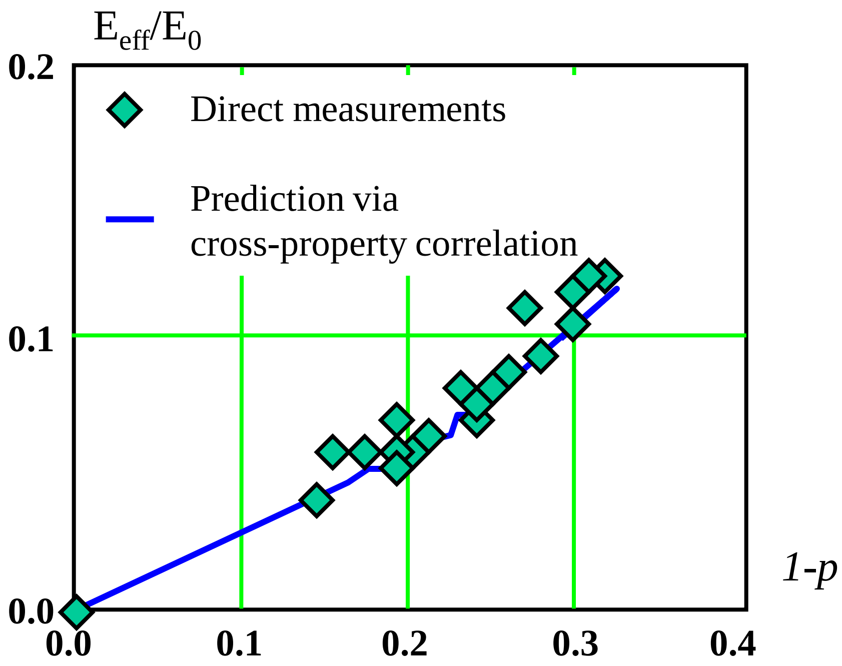
Aluminum foam

experiments were done at the Institute of Materials and Machine Mechanics, Slovak Academy of Sciences.



Two different geometries of the test specimens were used: cylindrical rods with a diameter of 25 mm and length 300 mm (for measuring modulus of elasticity) and flat plates with dimensions 140 x 140 x 8.5 mm (for measuring electrical conductivity).

The degree of the anisotropy of electric conductivity was found to be smaller than 10%, therefore the sample can be considered as almost isotropic.



$$\frac{E_0 - E_{eff}}{E_{eff}} = \frac{(1-\nu_0)(9+5\nu_0)}{(7-5\nu_0)} \frac{k_0 - k_{eff}}{k_{eff}}$$

Agreement is better than 10%

Short fiber reinforced composites

Experimental data are taken from:

Choy, C.L., Leung, W.P., Kowk, K.W. and Lau F.P. (1992) Elastic moduli and thermal conductivity of injection molded short-fiber reinforced thermoplastics, *Polymer Composites*, **13**, 69-80

Full set of orthotropic elastic and conductive constants of thermoplastics (polyphenilene sulfide, PPS) reinforced by short glass fibers (with the aspect ratio 16). The accuracy of the data was within 8%, for both elastic and conductive constants.

Properties of constituents

	Glass fibers	Polymer matrix
E (GPa)	76	4.0
G (GPa)	30.4	1.43
ν	0.25	0.4
K (mW/cm·K)	10.4	2.0

Experimentally measured thermal conductivities (mW/cm·K)

	30% of fibers	30% of fibers	40% of fibers	40% of fibers
K_1	2.86	2.95	3.24	3.22
K_2	2.62	2.97	2.79	3.18
K_3	3.82	3.69	4.08	3.99

Comparison of the effective elastic stiffnesses calculated using cross-property correlation (plane font) with experimental data (bold font)

	30% fibers	30% fibers	40% fibers	40% fibers
C_{11}	10.93/**11.4**	11.20/**12.2**	12.45/**12.1**	12.13/**13.0**
C_{22}	9.59/**10.7**	11.31/**11.2**	9.93/**11.5**	11.91/**12.0**
C_{33}	16.89/**18.9**	15.34/**17.5**	17.14/**24.7**	16.43/**21.2**
C_{44}	2.80/**2.57**	2.93/**2.79**	2.98/**2.72**	3.19/**2.95**
C_{55}	3.03/**2.72**	2.91/**3.82**	3.41/**3.12**	3.22/**3.45**
C_{66}	1.88/**2.06**	2.21/**2.18**	2.17/**2.40**	2.45/**2.65**
C_{12}	6.50/**6.2**	6.83/**6.4**	6.85/**7.1**	7.13/**6.9**
C_{13}	7.54/**6.9**	7.46/**6.7**	7.97/**7.5**	7.84/**7.2**
C_{23}	7.33/**6.5**	7.48/**6.6**	7.58/**7.1**	7.8/**7.1**

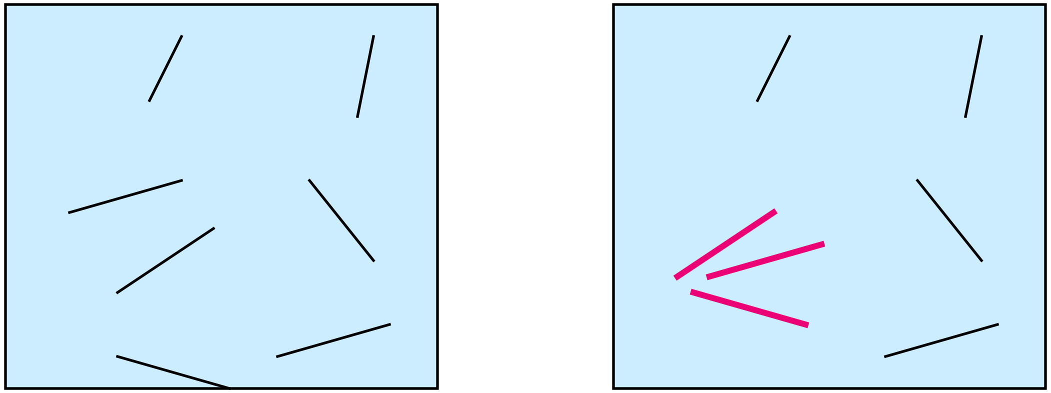
Negative message:

If microstructural parameters for two physical properties are

substantially different:

cross-property connection cannot be established

Fracture – elasticity



Sensitivity to clustering

low, for effective <u>elasticity</u>

high, for <u>fracture</u>

Microstructural parameters controlling them are essentially different

Loss of stiffness is <u>not</u> a reliable indicator of fracture process

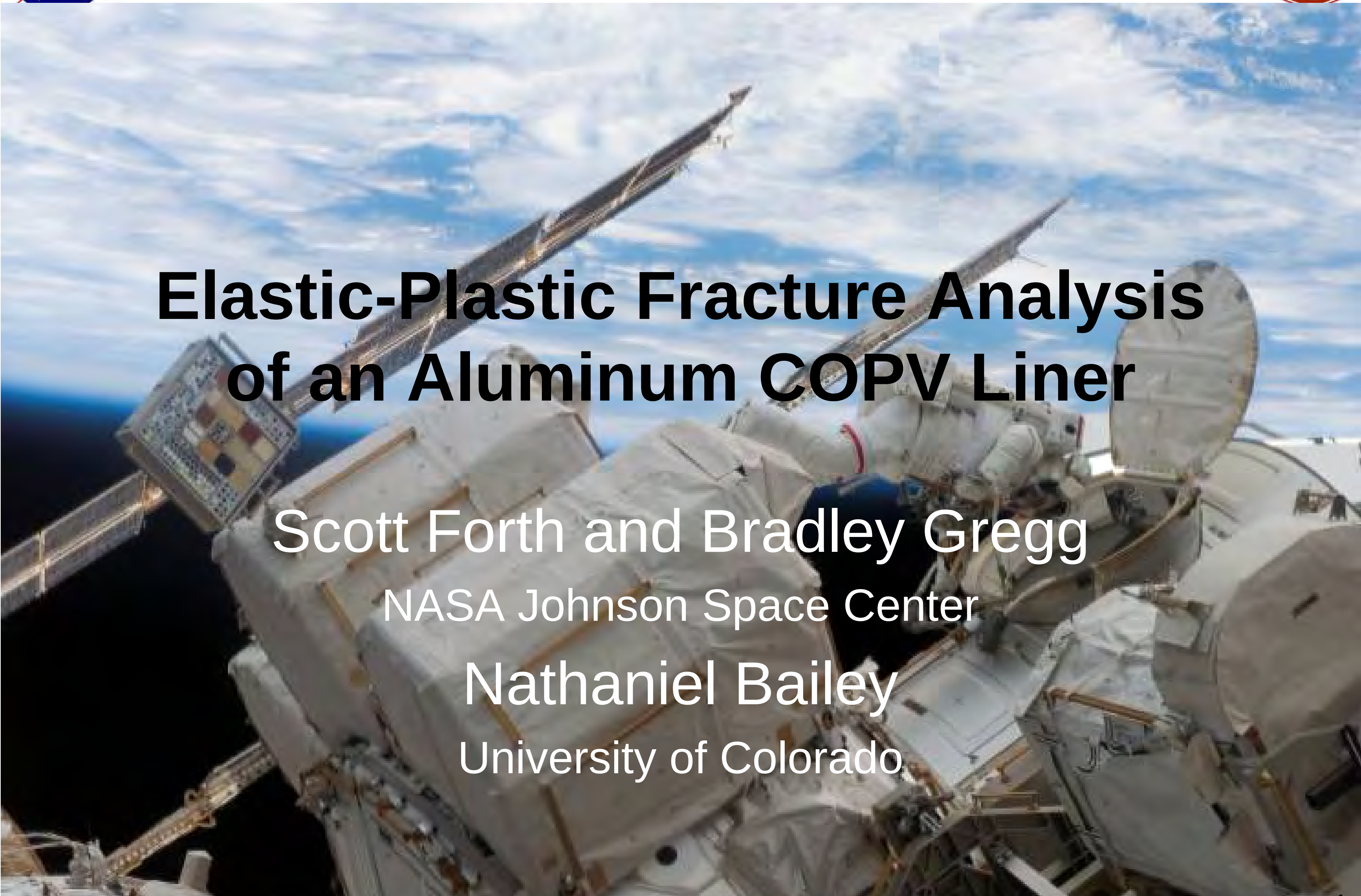
Conclusions

Explicit connections can be established between full sets of (anisotropic) elastic and conductive constants of materials with multiple inhomogeneities.

Experiments on diverse materials show that these connections, originally derived in the non-interaction approximation and for the ellipsoidal shapes, can actually be applied to **high concentrations of irregularly shaped inhomogeneities**.

Quantitative connections between strength reduction and decrease in elastic stiffness cannot be established.

NM STATE UNIVERSITY



Elastic-Plastic Fracture Analysis of an Aluminum COPV Liner

Scott Forth and Bradley Gregg

NASA Johnson Space Center

Nathaniel Bailey

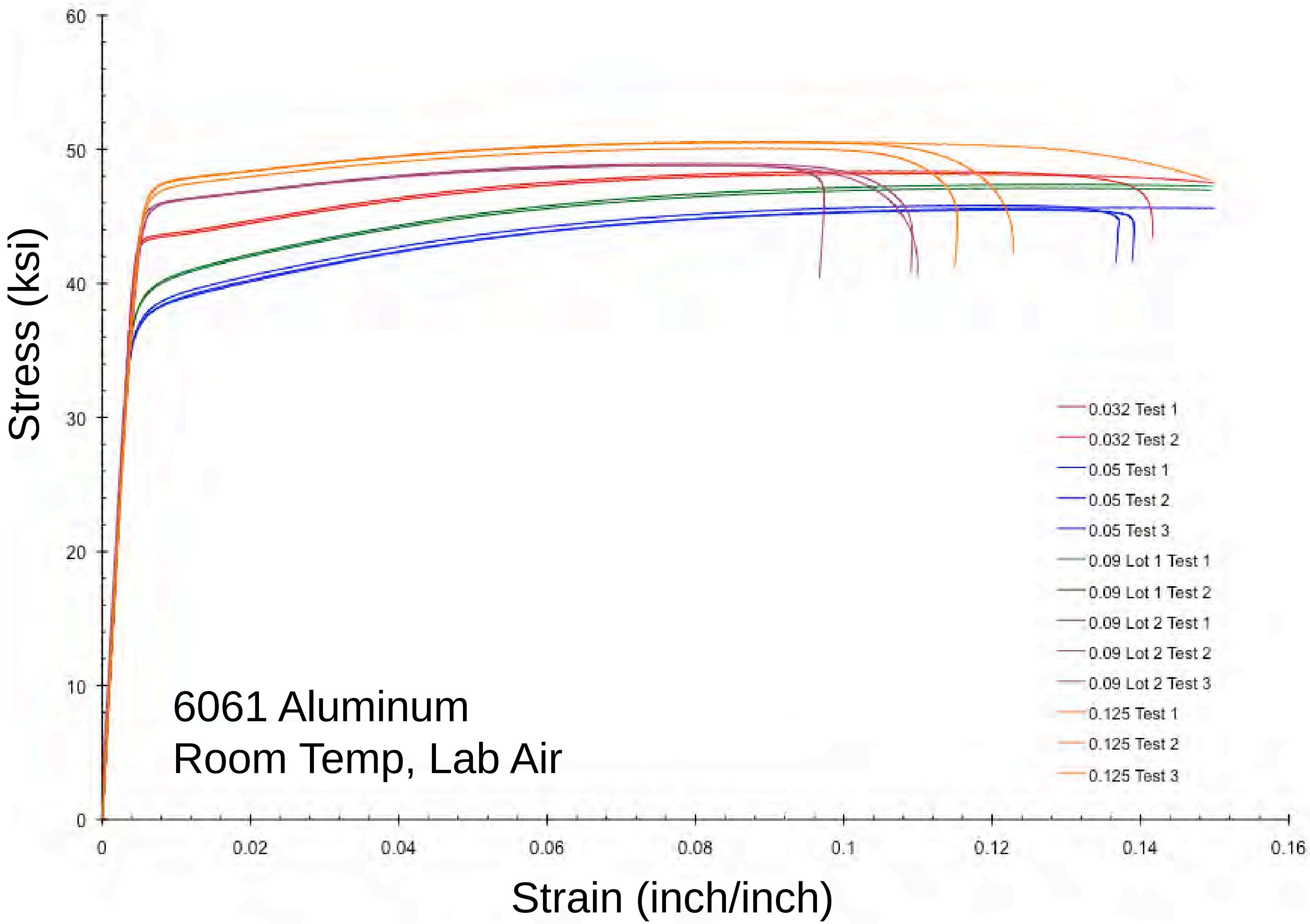
University of Colorado

S116E06937

Aluminum Liner

- Spun-form 6061 aluminum
- Specimens taken from sheet
- Uni-axial test data shown herein
- COPV testing not shown
- Data generated at NASA Langley Research Center (Dawicke, Lewis)
- Analysis performed at NASA Johnson Space Center

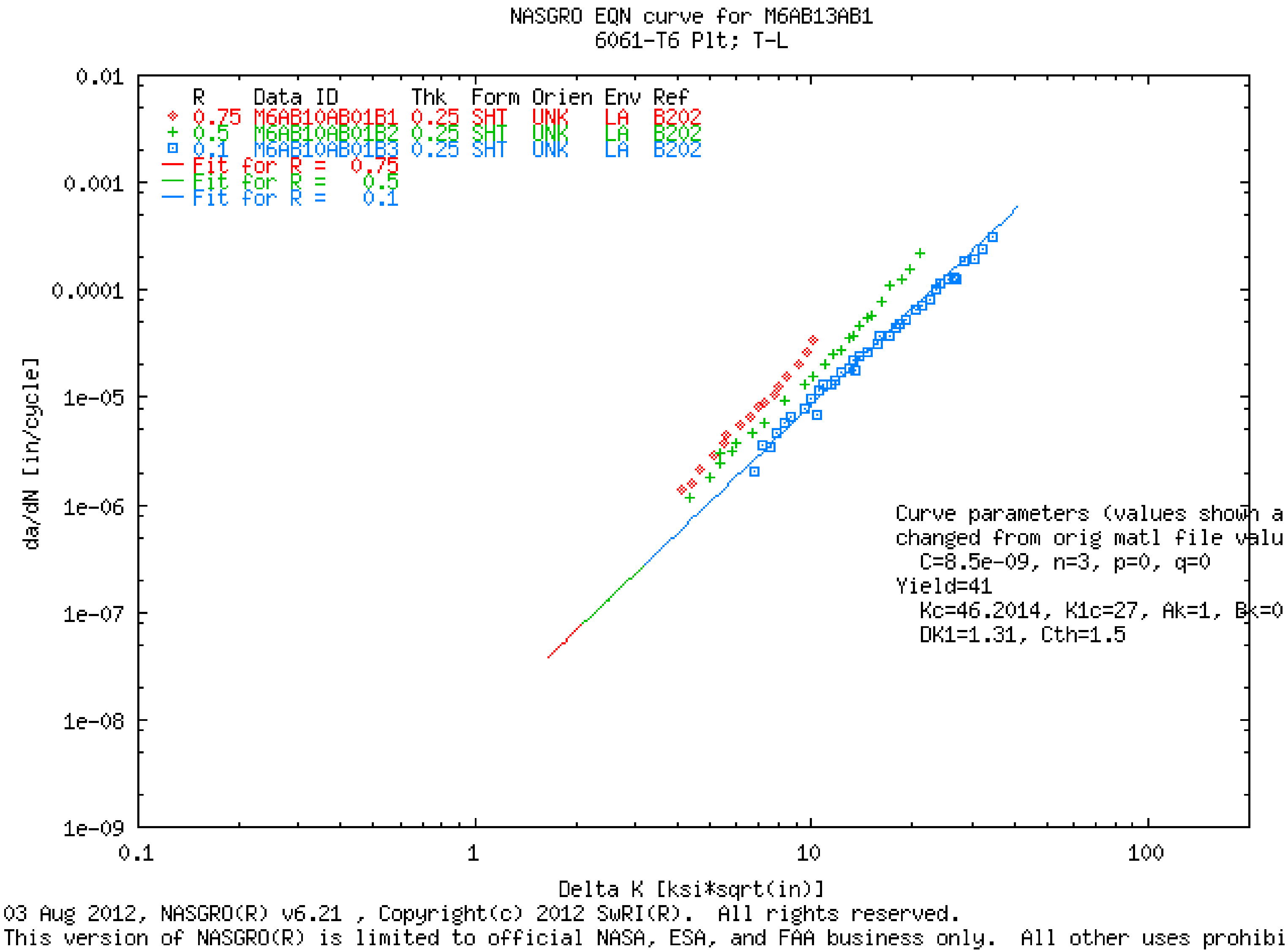
Stress Strain Response



Material Characterization

Thickness	Yield (ksi)	Ultimate (ksi)	Young's Modulus (Msi)	Alpha (R-O)	R-O Exponent
0.032	43.4	48.3	10.041	0.002	50
0.050	37.5	45.7	10.020	0.002	25
0.090 Lot 1	39.5	47.2	9.986	0.002	30
0.090 Lot 2	45.5	48.9	9.708	0.002	50
0.125	46.63	50.41	9.887	0.002	30

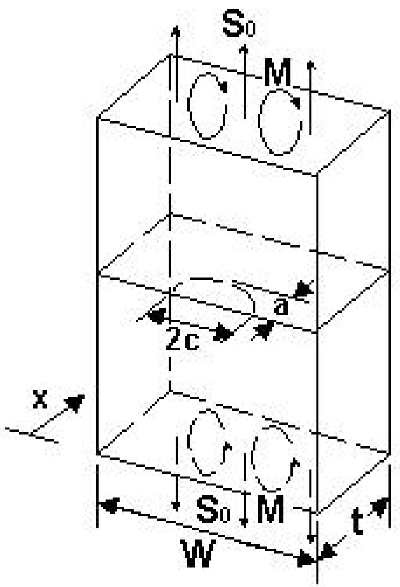
Crack Growth Rate



Elastic-Plastic Fracture Mechanics

- NASGRO 6.2 EPFM module

SC01



$$S_1 = \frac{6M}{Wt^2}$$

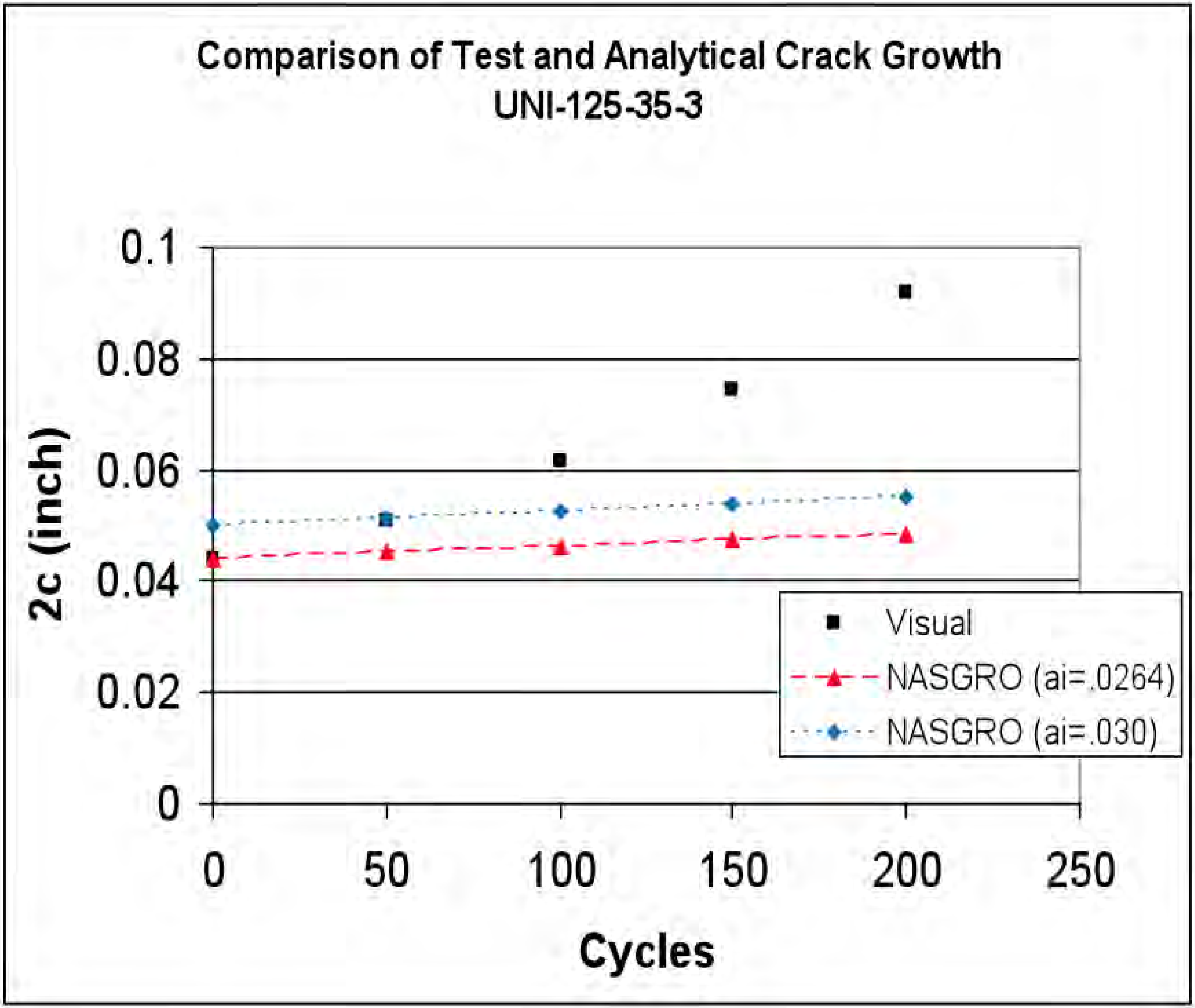
$$0 < \frac{2c}{W} \le 1$$

$$0.1 \le \frac{a}{c} \le 1.2$$

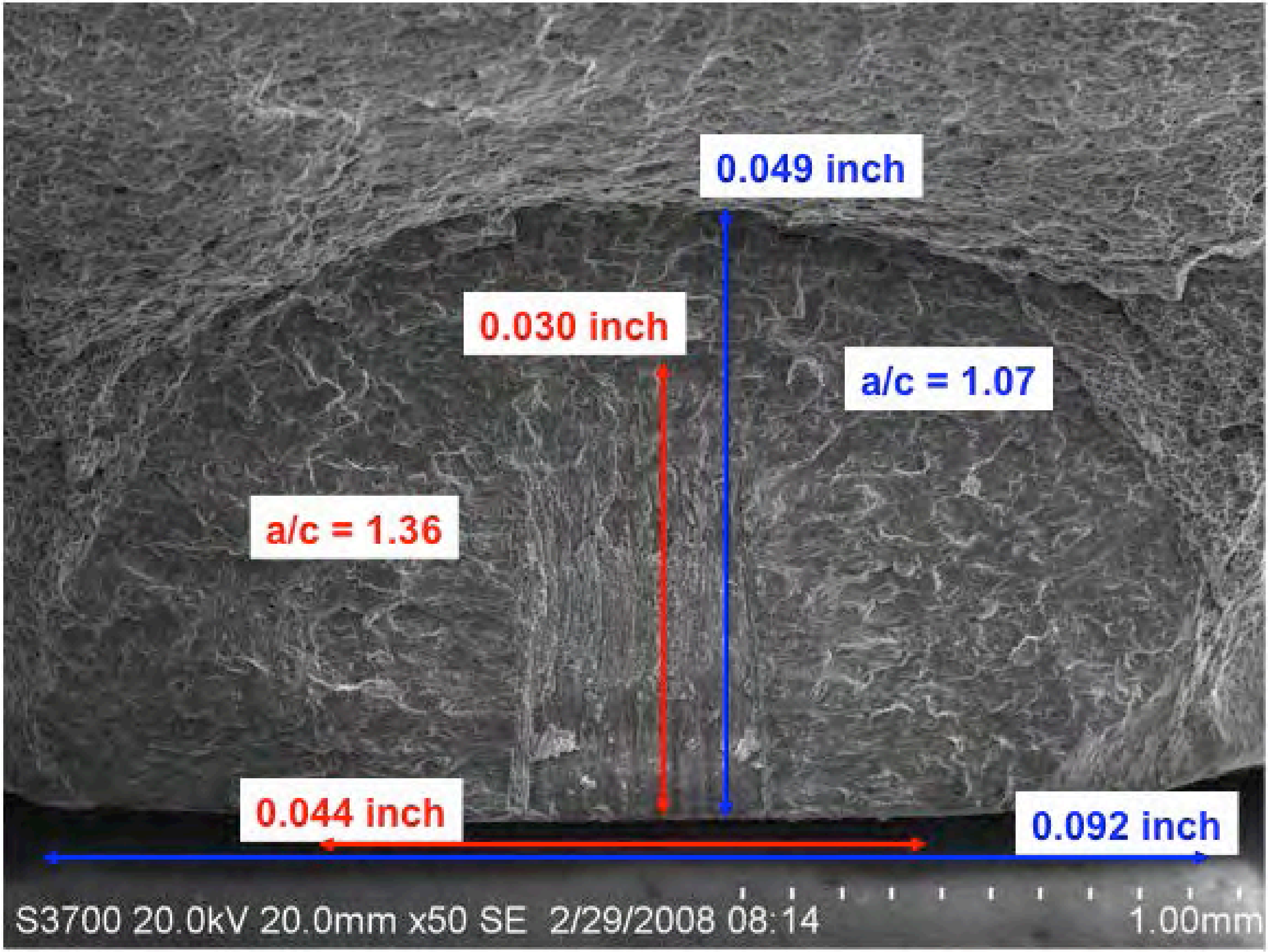
	Test Parameters			NASGRO Input		
Crack ID	Crack Length, c	Crack Depth, a	Crack Ratio, a/c	Crack Length, c	Crack Depth, a	Crack Ratio, a/c
UNI 050 35 1	0.0200	0.0260	1.3000	0.0200	0.0240	1.2000
UNI 050 35 4	0.0205	0.0280	1.3659	0.0205	0.0246	1.2000
UNI 050 35 5	0.0205	0.0260	1.2683	0.0205	0.0246	1.2000
UNI 090 35 1	0.0205	0.0340	1.6585	0.0205	0.0246	1.2000
COPV 090 35 2	0.0210	0.0350	1.6667	0.0210	0.0252	1.2000
COPV 090 35 3	0.0200	0.0340	1.7000	0.0200	0.0240	1.2000
COPV 090 36 1	0.0500	0.0120	0.2400	0.0500	0.0120	0.2400
COPV 090 36 2	0.0520	0.0200	0.3846	0.0520	0.0200	0.3846
COPV 090 36 4	0.0525	0.0200	0.3810	0.0525	0.5000	0.3800
UNI 125 35 1	0.0205	0.0340	1.6585	0.0205	0.0246	1.2000
UNI 125 35 2	0.0210	0.0310	1.4762	0.0210	0.0252	1.2000
UNI 125 35 3	0.0220	0.0300	1.3636	0.0220	0.0264	1.2000

NASGRO Input: Specimen Geometry				
Crack ID	Width (in)	Thickness (in)	Crack Length, c (in)	Crack Depth, a (in)
UNI 050 35 1	2.0000	0.0500	0.02000	0.0240
UNI 050 35 4	1.9950	0.0500	0.02050	0.0246
UNI 050 35 5	2.0000	0.0500	0.02050	0.0246
UNI 090 35 1	1.9600	0.0900	0.02050	0.0246
COPV 090 35 2	1.9700	0.0900	0.02100	0.0252
COPV 090 35 3	1.9800	0.0900	0.02000	0.0240
COPV 090 36 1	2.0250	0.0900	0.05000	0.0600
COPV 090 36 2	2.0000	0.0900	0.05200	0.0624
COPV 090 36 4	2.0000	0.0900	0.05250	0.0630
UNI 125 35 1	1.9400	0.1250	0.02050	0.0246
UNI 125 35 2	2.0200	0.1250	0.02100	0.0252
UNI 125 35 3	1.9850	0.1250	0.02200	0.0264
MT 1	3.0300	0.0900	0.24025	0.0900
MT 2	3.0300	0.0900	0.24175	0.0900
MT 3	2.9900	0.0870	0.27600	0.0870

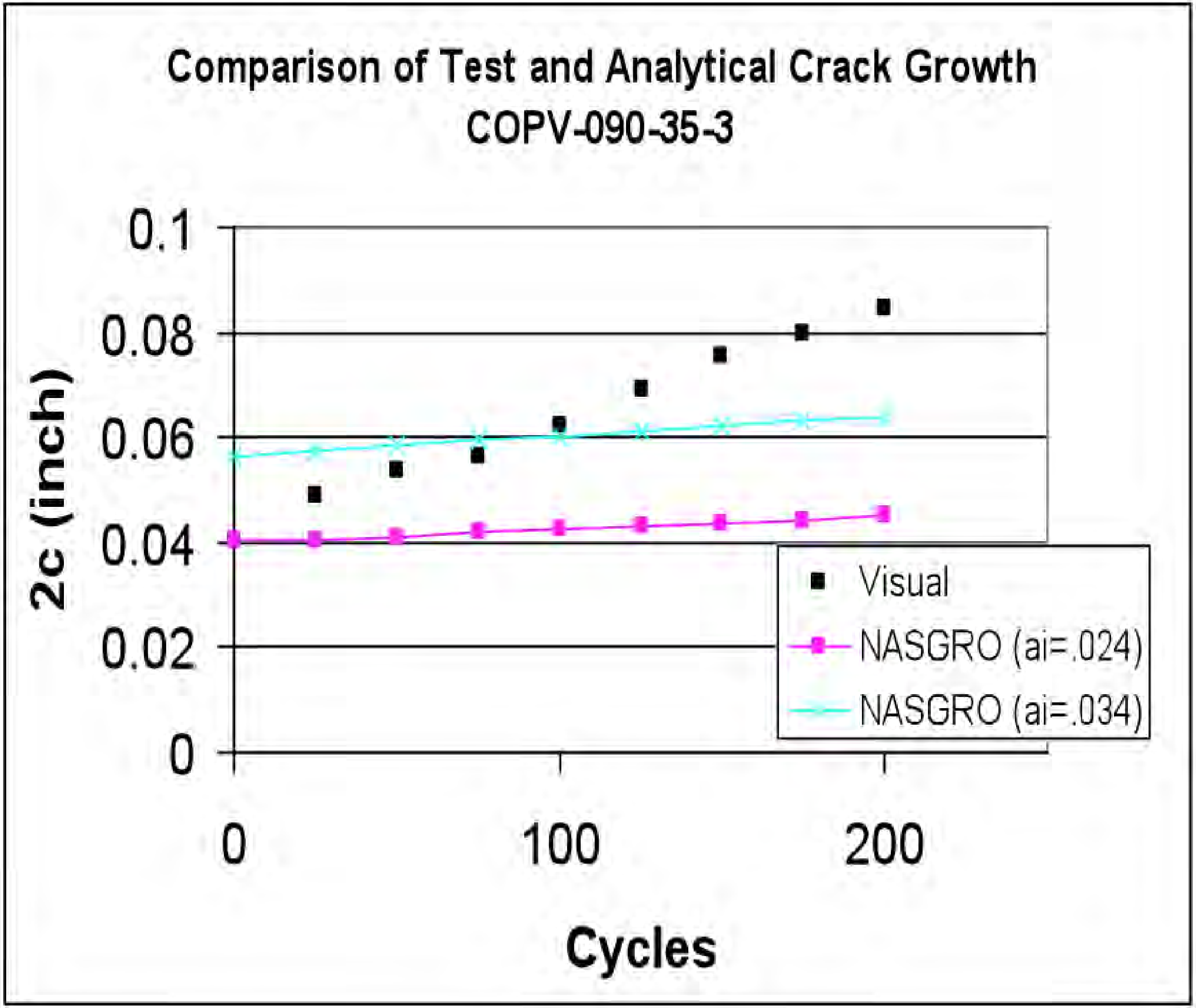
0.125" Uniaxial Test Data



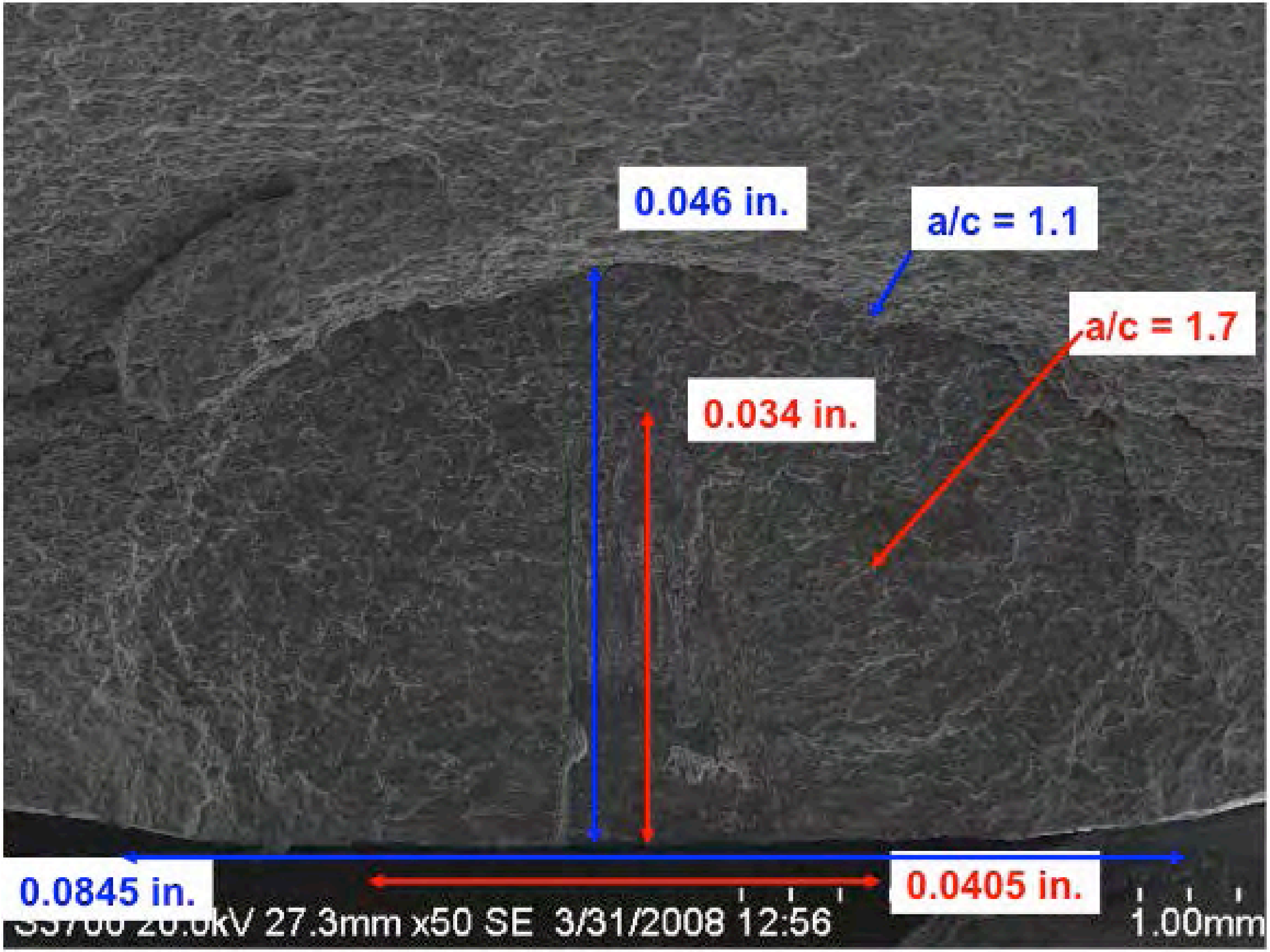
0.125” Fracture Surface



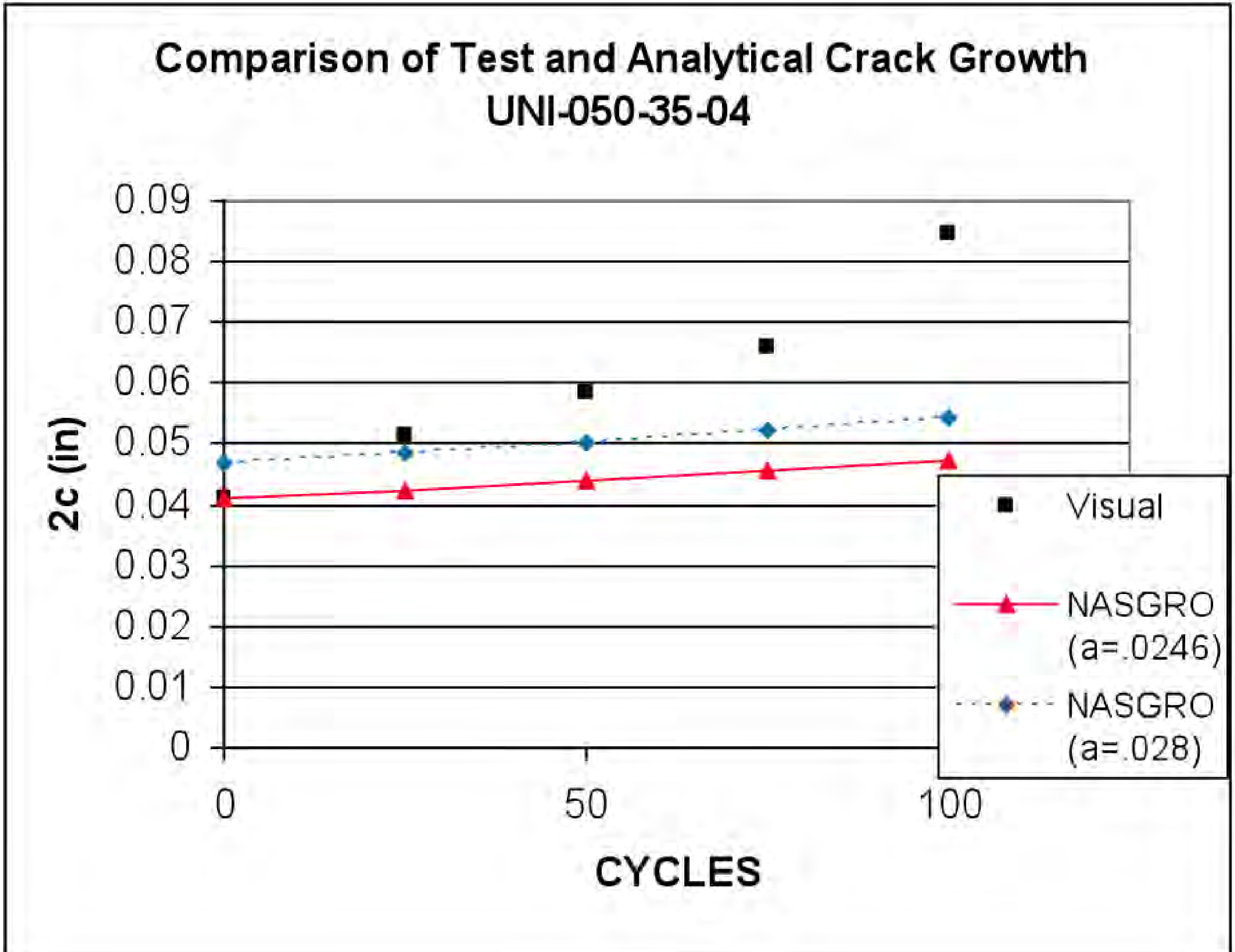
0.090” Uniaxial Test Data



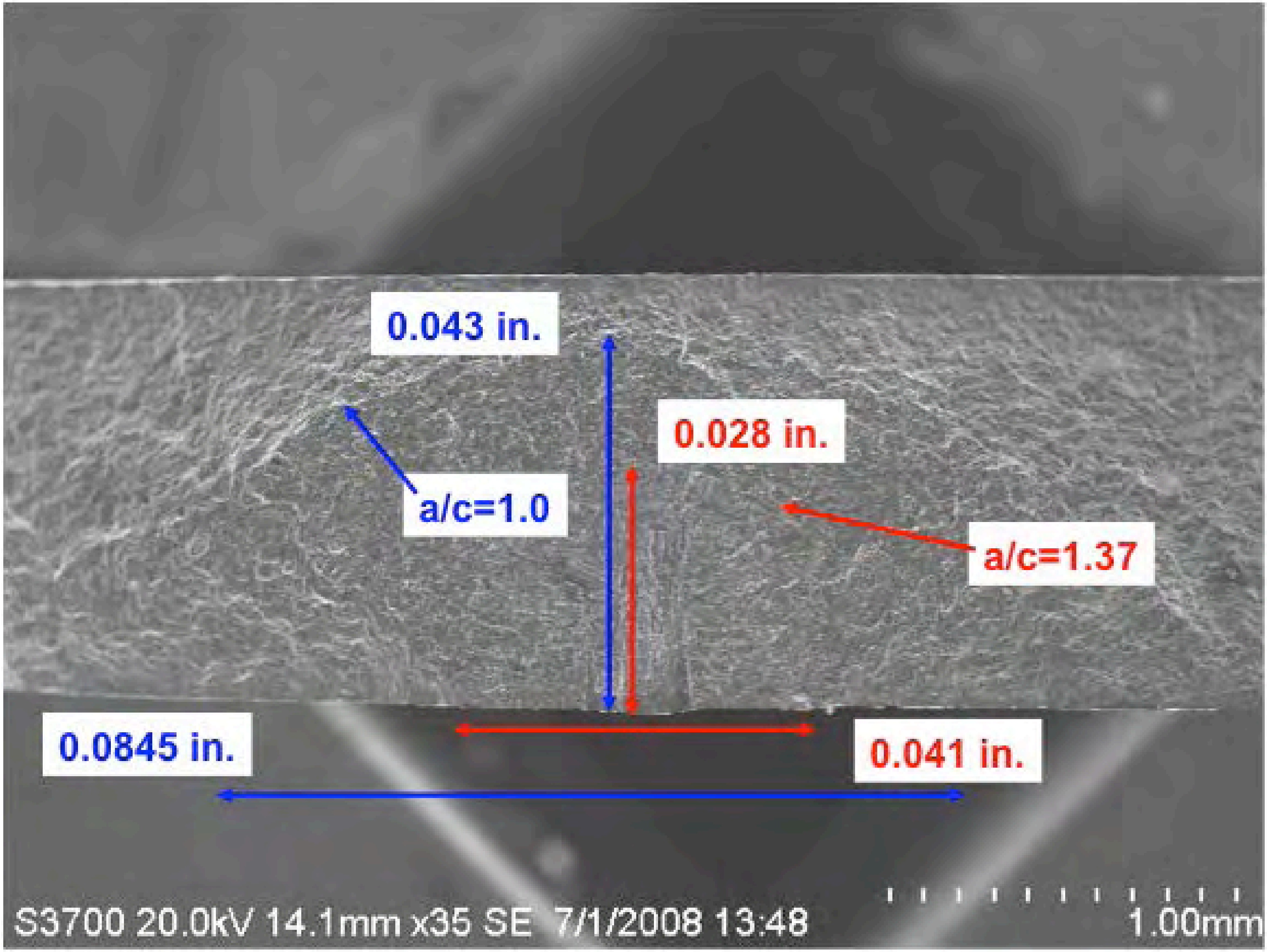
0.090" Fracture Surface



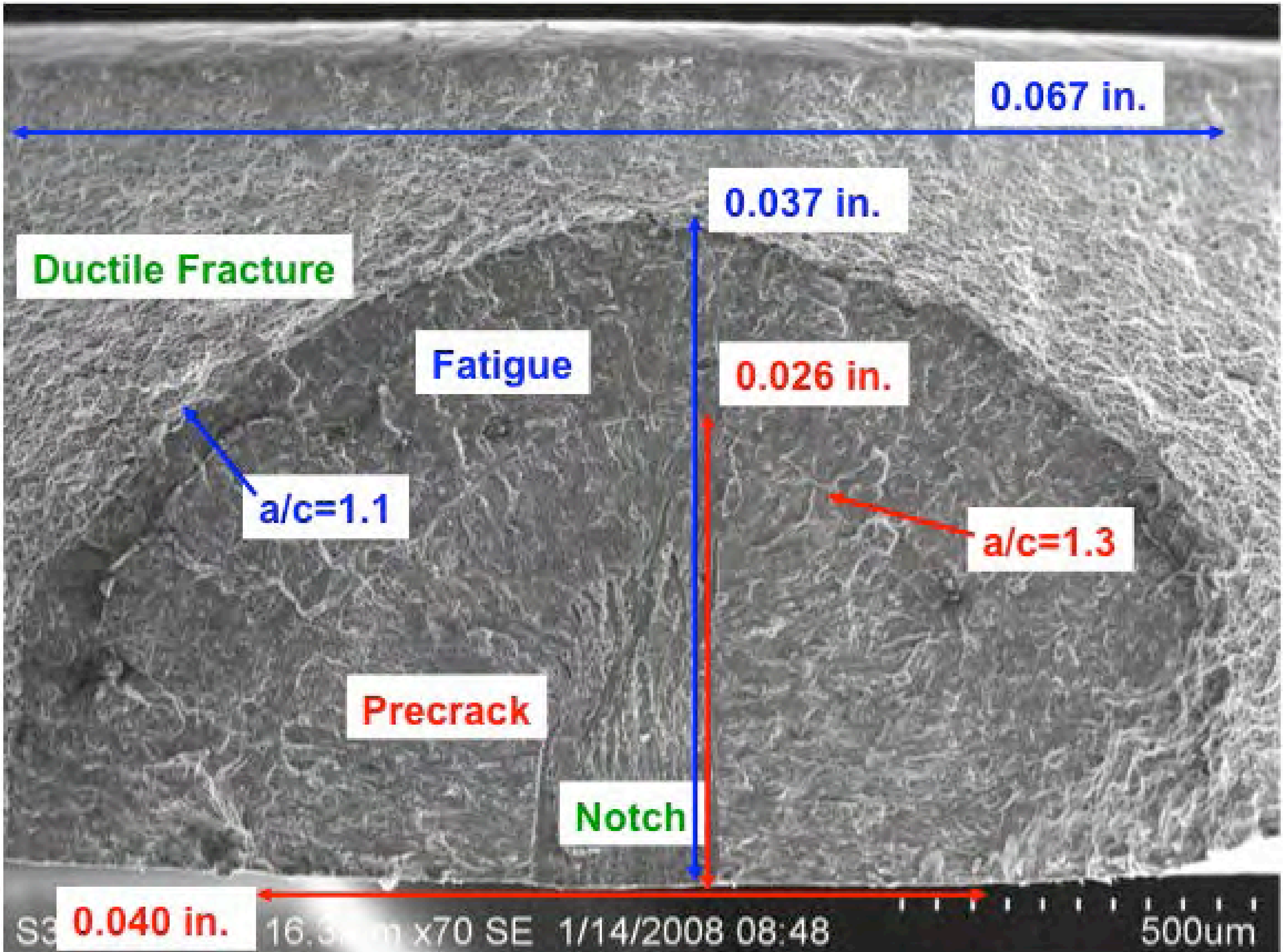
0.050" Uniaxial Test Data



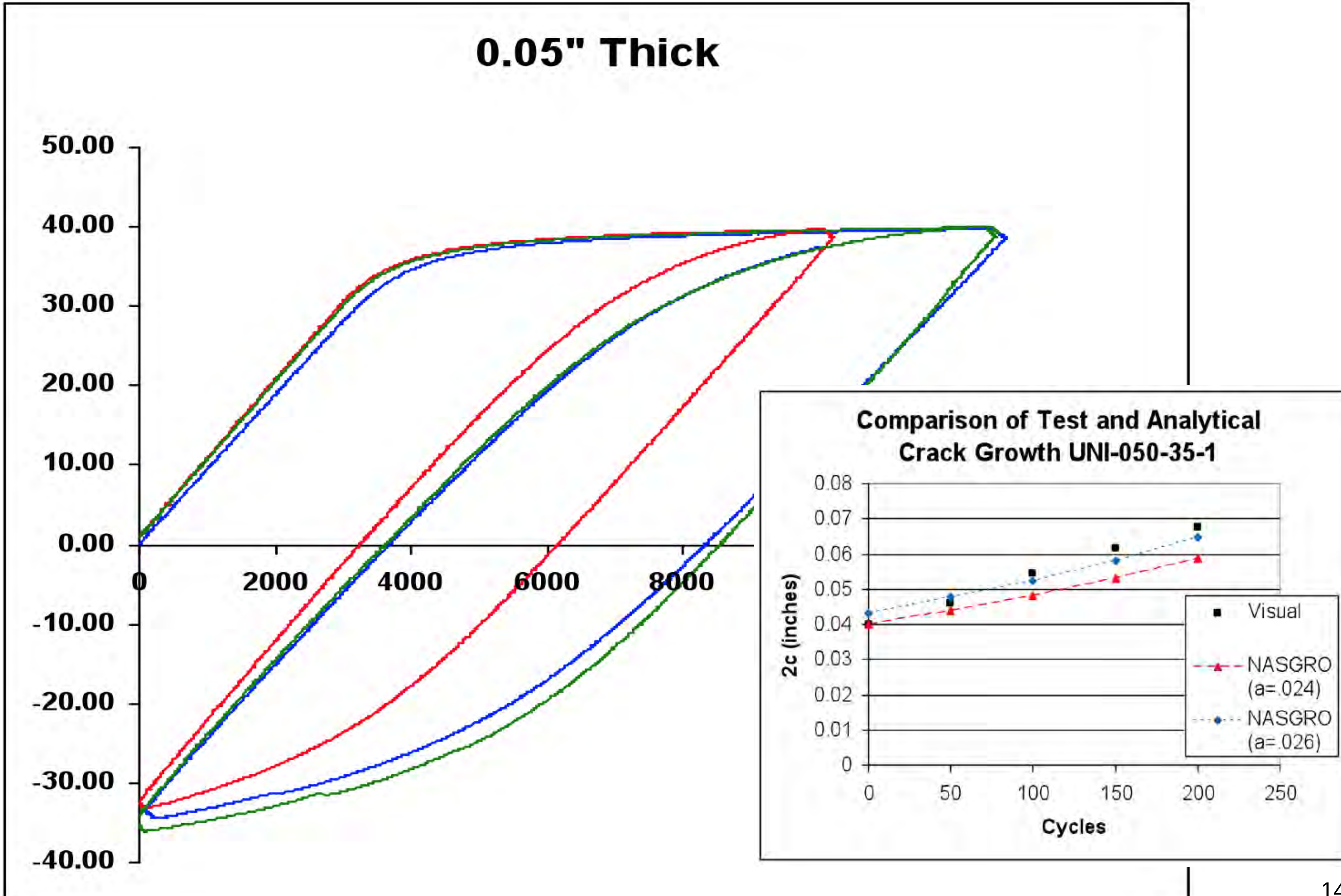
0.050” Fracture Surface



Token Promising Result



Promising Analytical Result



Summary

- Elastic plastic fracture analyses

Pros:

  - Results are promising when crack is self-similar
  - Additional testing needed to verify approach
  - Long-term goal of analytical certification

Cons:

  - Material data is difficult to obtain and reduce for NASGRO input
  - Stress input is not consistent with strain-controlled COPV liner

- Forward work
  - NASA is funding an upgrade to the EPFM module
  - EPFM testing is being performed for flight vehicles

Delamination Assessment Tool For Spacecraft Composite Structures

Gerben Sinnema et al.
Composite Conference 2012
14 Aug '12

Delamination Assessment Tool
For
Spacecraft Composite Structures

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This presentation summarizes a study, performed within the ESA TRP Programme:

Delamination Assessment Tool for Composite Structures

(ESA contract 22789/09/NL/RA)

It was performed with the contribution of the following industrial and academic partners:

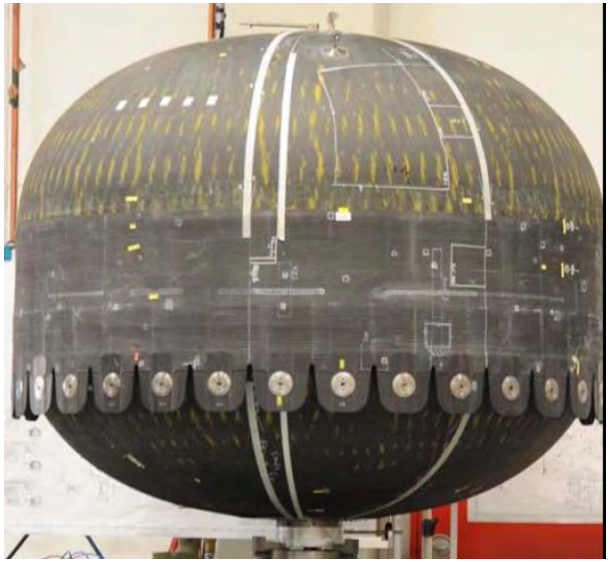
HPS Lda	PORTUGAL (Prime contactor)
INEGI, Universidade do Porto	PORTUGAL
AMADE, Universitat de Girona	SPAIN
MT Aerospace	GERMANY
RUAG	SWITZERLAND
INVENT	GERMANY
DLR	GERMANY
University of Patras	GREECE

Note: Responsibility for the contents of this presented work resides in the author or organization that performed it.

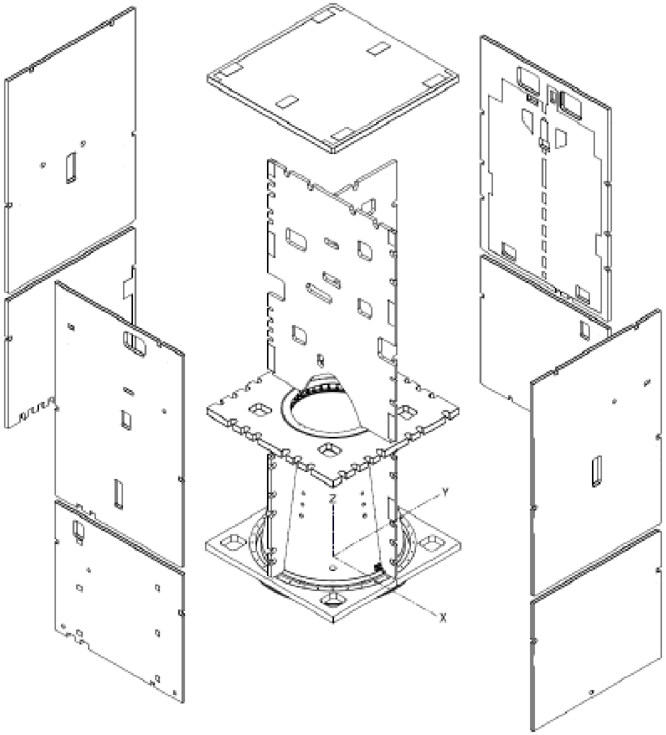
Introduction

- Since delaminations can be a real problem for structures made of composite materials, it was deemed necessary to develop a tool which can help the Agency as well as the industry identify this problem and its effects in an efficient and effective way.
- An ESA TRP was awarded in 2009 to HPS Portugal with various industrial and research partners.
  The activity is planned to finish in 2013.
- Objectives: To develop a comprehensive damage tolerance verification logic for highly loaded composite spaceflight structures, in particular for delaminations, addressing both numerical methodologies as well as material-, subcomponent- and component testing.
  The activity targets primarily unmanned spacecraft and launcher structures.

Spaceflight Structures - Examples



Composite propellant tank with composite attachment skirt



Satellite structures: composite cylinder, panels, struts, etc.

Launchers: composite SRM, interstages, adapters, fairings, etc.

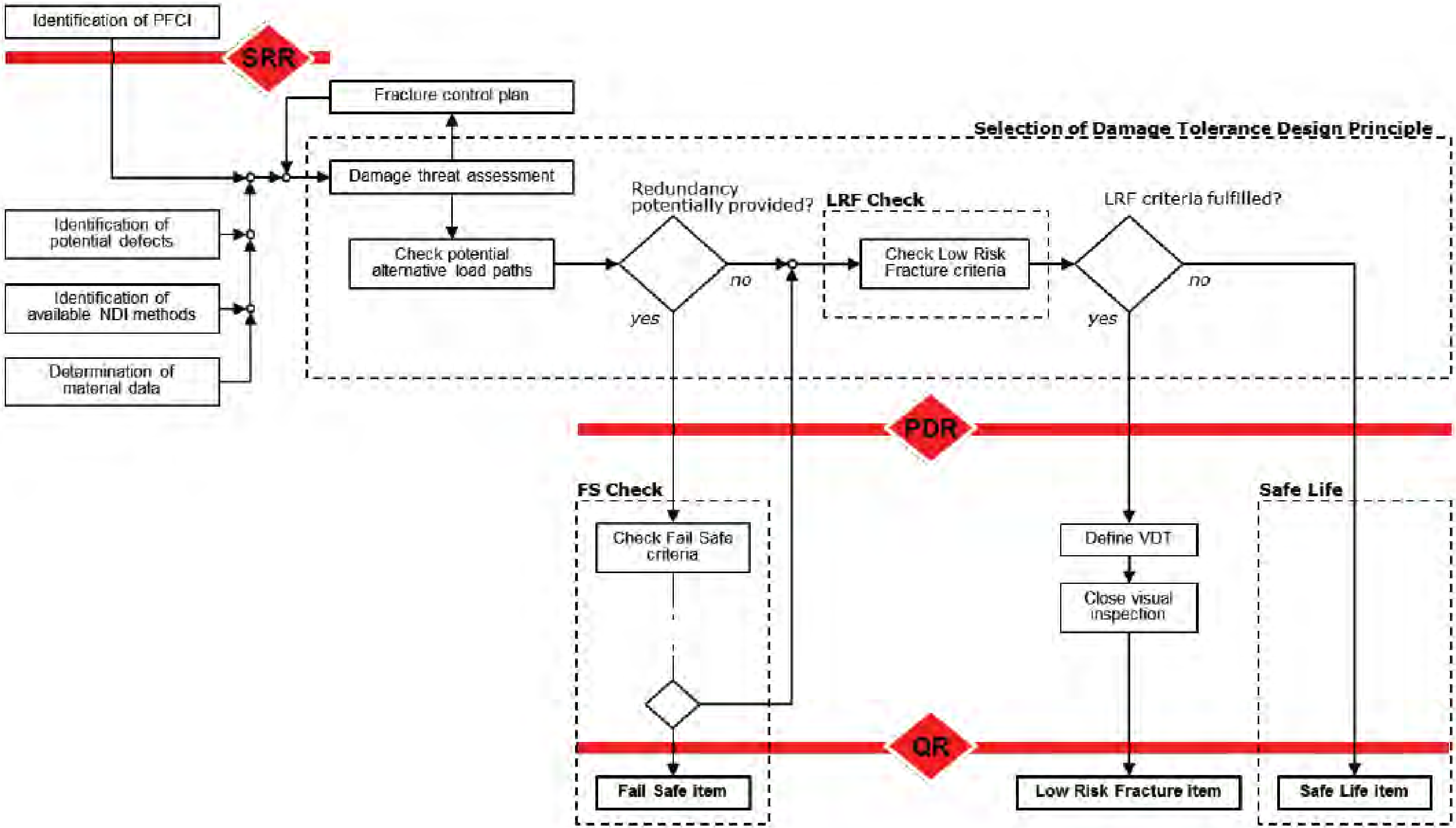
Introduction

- Output of the activity will include:
  - ‘TN-300 - Damage Tolerance Verification Approach and Best Practice Guidelines’, currently in draft issue.
  - ‘TN410 - Best Practice Analysis Methods’ (first issue is available from http://delat.inegi.up.pt/documents.asp)

Damage Tolerance Verification Approach

- The activity addresses a generic damage tolerance approach for composite, bonded and sandwich structural items, according to ECSS-E-ST-32-01C ‘Fracture Control’.
- Fracture control of potential fracture critical items relies on the techniques of safe life assessment, containment, fail safe assessment, proof testing, etc. See chart of next slide.
- It must be considered that fracture control aims to complement and not replace high quality manufacturing, process and product control, and integration practices.
- The damage tolerance approach has to address a wide range of structural/interconnection concepts, with or without redundancy, size, safety factors and margins, etc.

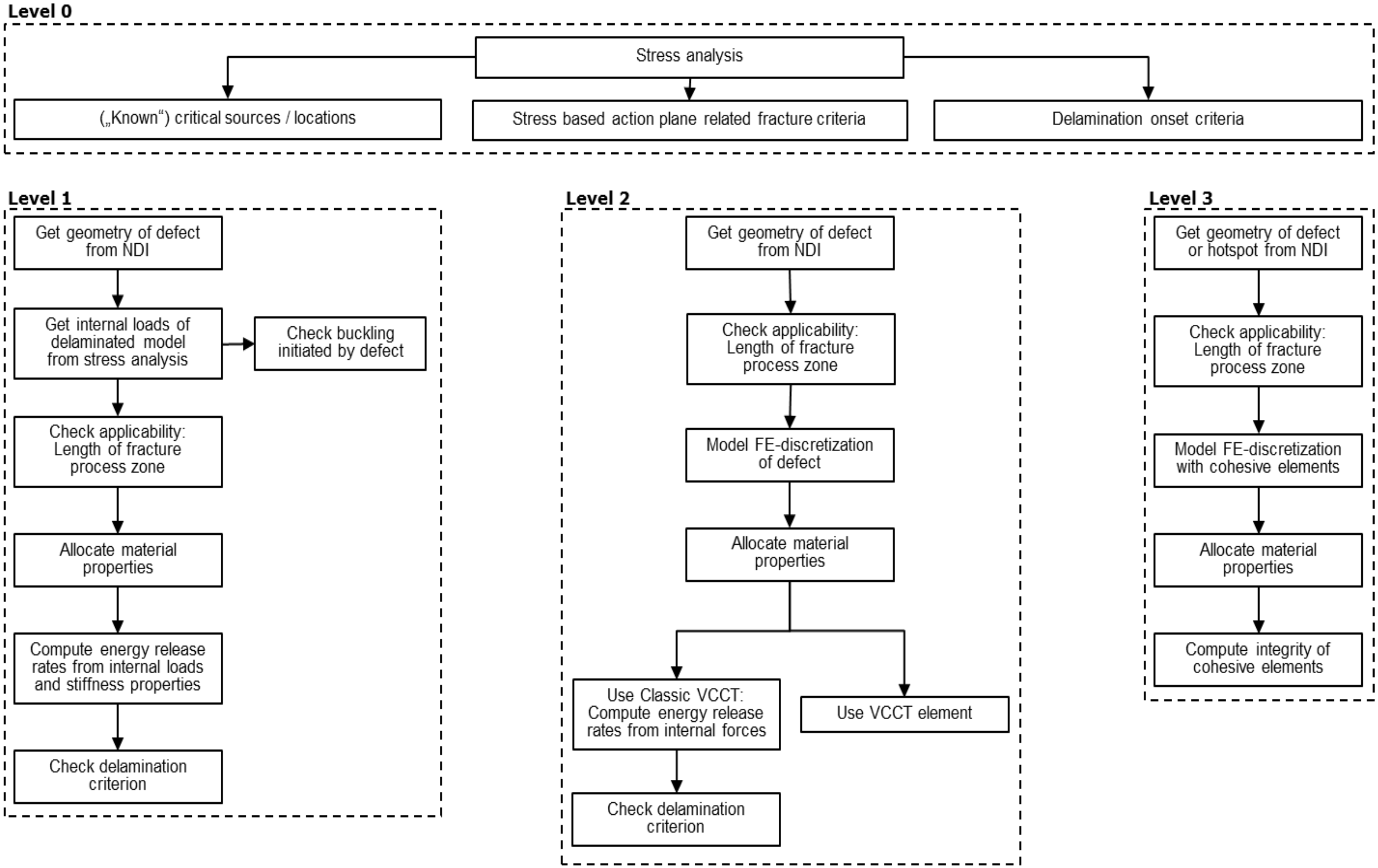
Damage Tolerance Verification Chart



Analysis Methods for Approaching Delamination Verification

- 3 analysis levels are proposed:
  - Level 1: Crack-tip elements (CTE)
  - Level 2: Virtual Crack Closure Technique (VCCT)
  - Level 3: Cohesive elements
- These advanced analysis methods are complemented by ‘Level 0’ assessment.
  The ‘Level 0’ assessment helps to establish the potential criticality of relevant delaminations, and to select the type (linear, non-linear), level (1, 2 or 3), locations and level of detail (mesh size, type of elements, …) of further analysis to be performed.
  In certain less critical cases, ‘Level 0’ assessment can make further Level 1-3 analysis obsolete.

Analysis Methods for Approaching Delamination Verification



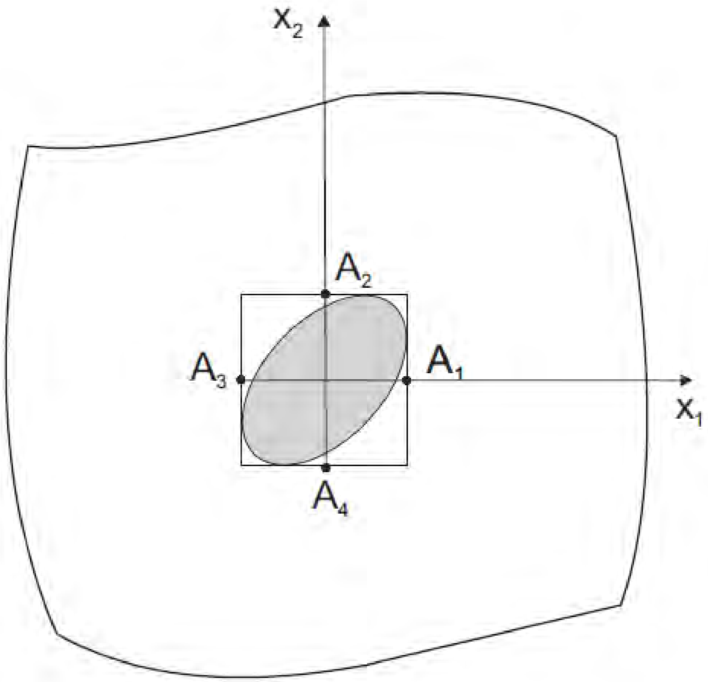
Level 0: Static Linear Model

- Identification of the most critical locations for delaminations to occur
    - Stress Analysis (evaluation of failure criteria, stress state, etc)
    - Ye's Criterion (interlaminar stress assessment of undamaged structure)
- Required before user can perform either level 1, 2 or 3 analysis.
- The goal is to complement this with a range of simple assessment methods, rules of thumb, experience from similar structures, etc. in order to target the more elaborate level 1-3 analysis only at the most critical cases.

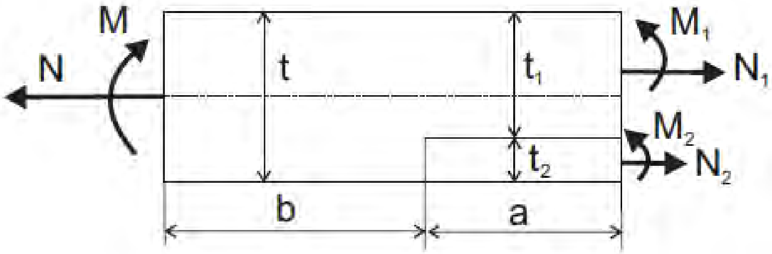
Level 1: Crack-Tip Elements

- Based on simple closed-form solutions
- Requires few material properties and a pre-cracked analysis model
- Geometry of the initial delamination is normally based on NDI capability.
- Analysis method is conservative, provided that the driving force is properly represented in the analysis.
  In case buckling is significant, non-linear analysis may be required!
- Does not require expert users. The user has to be able to judge whether delamination buckling may be of significance.
- Provides a solution in a short amount of time.
- For simple fracture mechanics test coupons, this method predicts with remarkable accuracy the energy release rate.

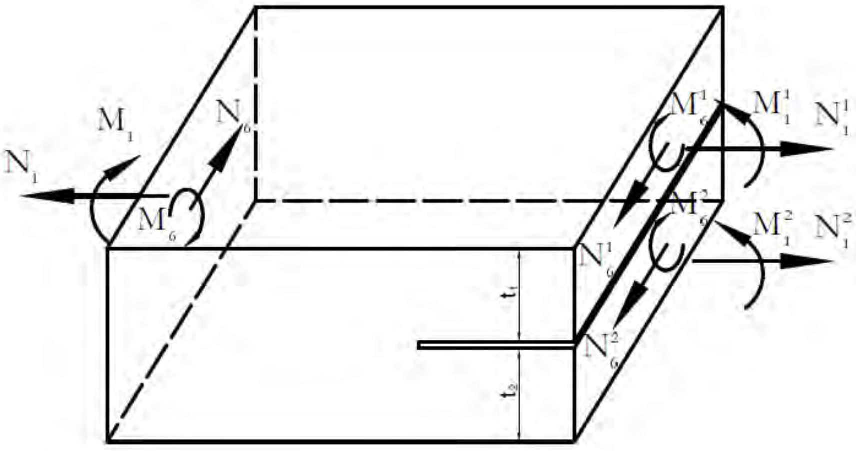
Level 1: Geometry and Loading



Delaminated region



2D crack tip element



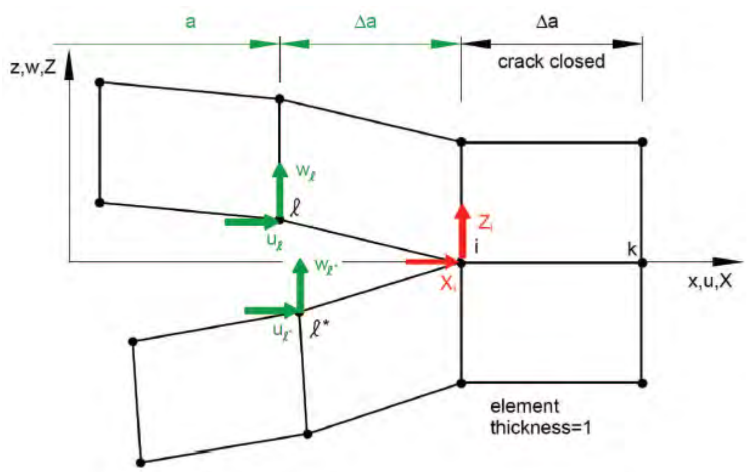
3D crack tip element

Level 2: Virtual Crack Closure Technique (VCCT)

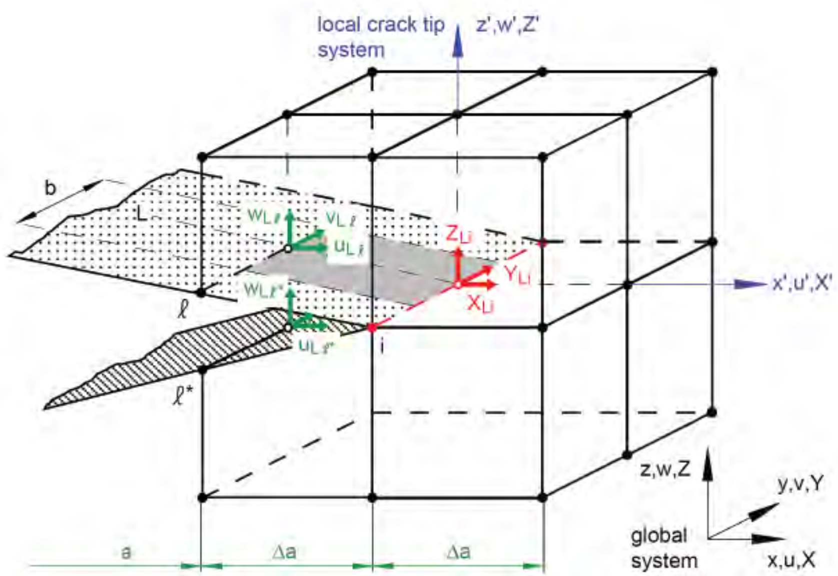
- Reduces conservatism of level 1, it is a more detailed analysis
- Geometry required is the same as CTE and the Mode III fracture toughness is required as additional material property
- Requires pre-crack, just as the CTE of level 1
- VCCT based on linear-elastic Finite Element (FE) models, applicable when linear-elastic fracture mechanics conditions prevail
- Can be used for the simulation of delamination in any structure or material
- Except when the prediction of buckling driven delamination is sought, in this case a geometrically non-linear analysis is required
- Conservative prediction (based on toughness parameters) for materials with large fracture process zones

Level 2: Classic VCCT

Two and Three Dimensional Analysis



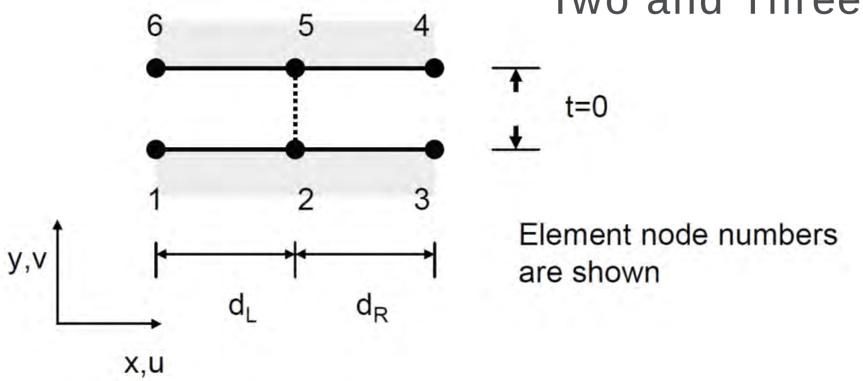
VCCT for 4-noded elements



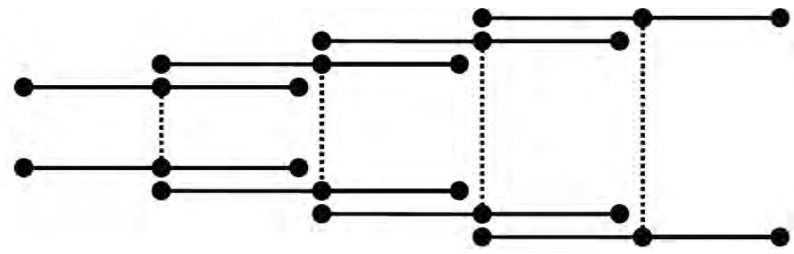
VCCT for 8-noded elements

Level 2: VCCT Element

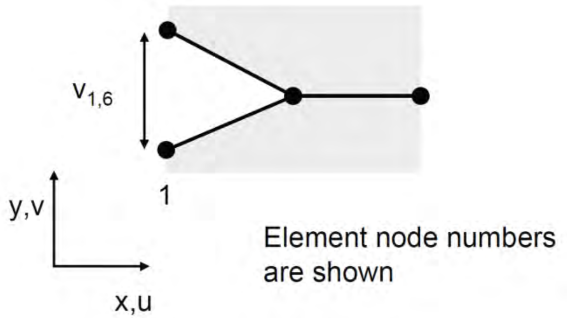
Two and Three Dimensional Analysis



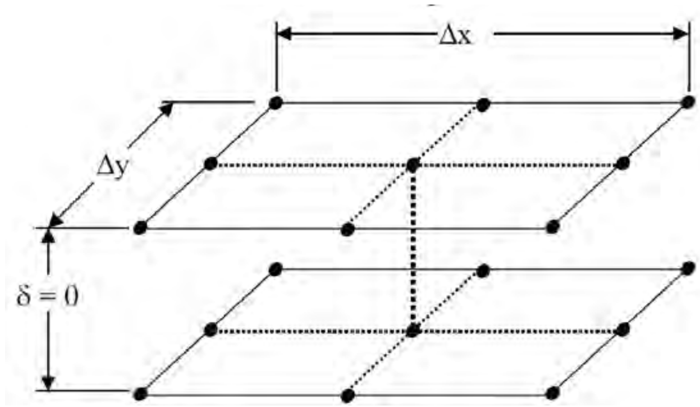
Undeformed planar VCCT element



Series of VCCT elements



Deformed planar VCCT element
prior to start of node release



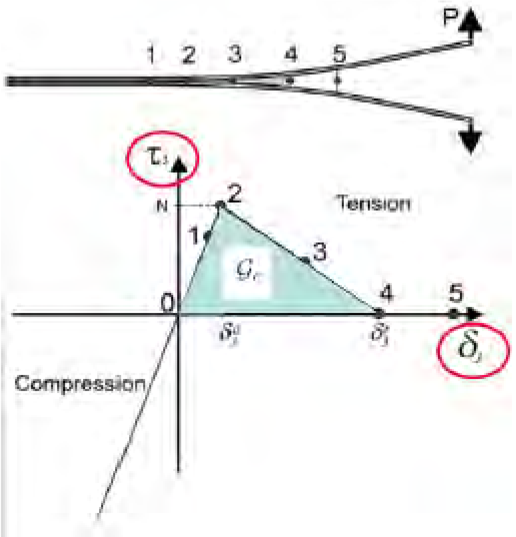
3D VCCT elements

Level 2: Virtual Crack Closure Technique (VCCT)

- Care must be taken in selecting the element size at the crack tip when using the VCCT.
- Ranges of $\Delta a/t$ (t is the nominal thickness of an individual ply and Δa is the dimension of the element that represent the crack tip along the crack propagation direction) are needed where the variation of the individual mode energy release rates is small: Values of $\Delta a/t$ greater than 0.1 and smaller than 1.0 are recommended.

Level 3: Cohesive Elements

- Most complex analysis method
- Requires users experienced in the use of non-linear FE codes.
- Most general analysis method
- Able to predict delamination onset and growth without requiring pre-cracks
- Fatigue driven delamination
- Stability of delamination growth.
- The geometry required is the same as it was for level 2 plus the through the thickness strengths and interface stiffness
- As with the other levels, NDI is required for delamination geometry.



Level 3: Cohesive Elements

- Care must be taken in selecting the element size at the crack tip when using cohesive elements.
- Cohesive finite elements require very fine meshes: at least three cohesive elements must be used on the fracture process zone to ensure accurate predictions.
  For example, the length of the fracture process zone for delamination in a unidirectional test specimen can be estimated in dependence of material parameters as Young's modulus, critical strain energy release rate and through-the-thickness strength.

Analysis Level Trade-offs

Material properties required for the different methods

	$\mathcal{G}_{Ic}$	$\mathcal{G}_{IIc}$	$\mathcal{G}_{IIIc}$	η	τ_1^0	τ_2^0	τ_3^0	# tests
Level 1	×							5
Level 2	×	×	×	×				15
Level 3	×	×	×	×	×	×	×	25

These are the number of tests that must be performed for each level of analysis to gather all the necessary material properties. Following the ASTM standards for these tests

	Stability	Buckling	Fatigue
Level 1	Requires 2 analysis	Limited	Only no-growth
Level 2	Requires 2 analysis	Yes, manual*	Only no-growth
Level 3	Automatically captured	Automatically captured	Full fatigue life

*automatically captured using the VCCT element.

	Large fracture process zones	Combination with ply failure mech.
Level 1	Not applicable.	Not applicable.
Level 2	Not applicable.	Limited.
Level 3	Applicable.	Automatic.

Application of the different methods

Case Studies Performed

Case Study 1: Satellite Structure (RUAG)

Levels Applied: Level 0, 2 and 3

Case Study 2: Satellite Propellant Tank (MT Aerospace)

Levels Applied: 0, 2

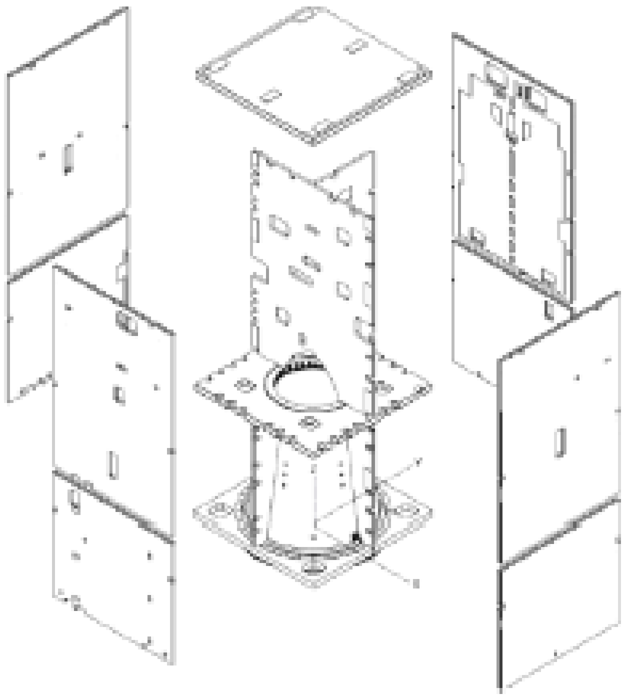
Case Study 3: Helicopter Structure (Invent)

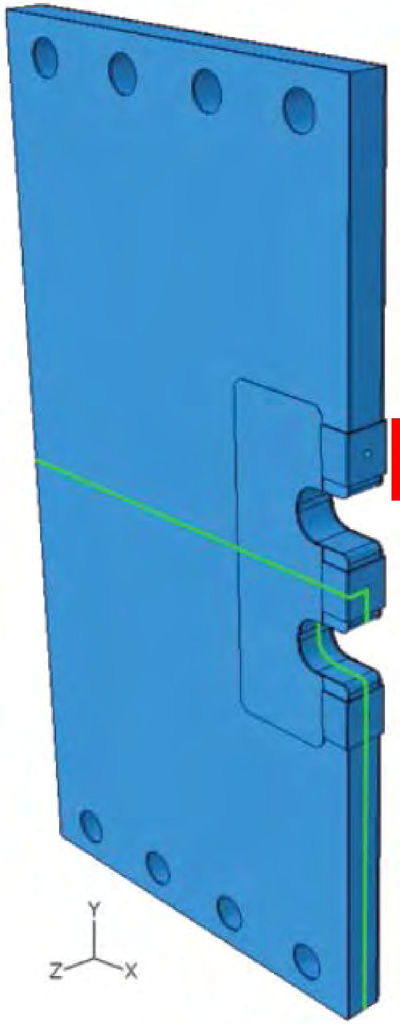
Levels Applied: 0, 1 and 2

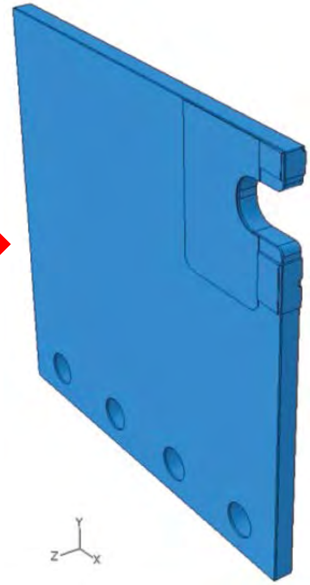
Case Study 1: Satellite Structure

- Sample panel derived from real-world satellite
- Standard primary structure sandwich panel made of CFRP face sheets and aluminium honeycomb core with a harness cut-out, connection cleats and doublers
- Can be modelled with 3D solid elements:
  - Actually only a quarter was modelled to avoid meshing issues,
  - obtain a more detailed mesh and improved accuracy
- All levels of analysis can be applied
- Various load types applied (structural, thermal)

Case Study 1: Satellite Structure







Case Study 1: Finite Element Analysis

1. Level 0: performed to identify the critical zones for delamination onset using Ye's criterion.

2. Level 2: Classic VCCT and VCCT Element models using Abaqus VCCT built-in capability

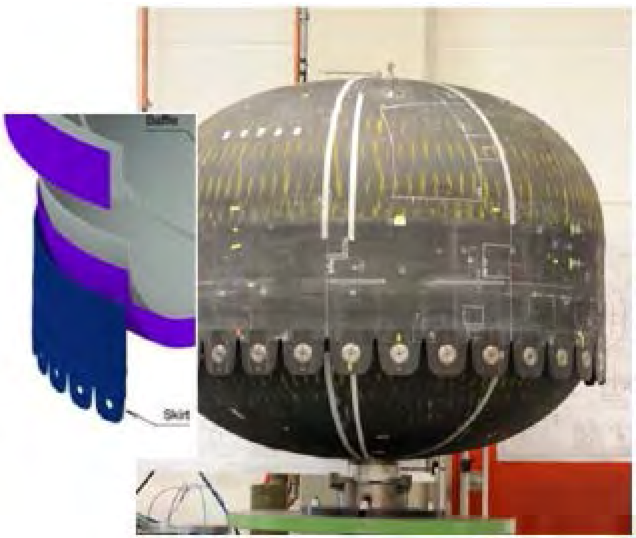
3. Level 3: does not need level 0 analysis, able to predict critical delamination location, which are the same as those identified by the level 0 analysis.

Location of delamination onset and growth direction is the same on levels 2 and 3, however the propagation was more conservative on level 3 than level 2 (may be due to differences in modelling strategy)

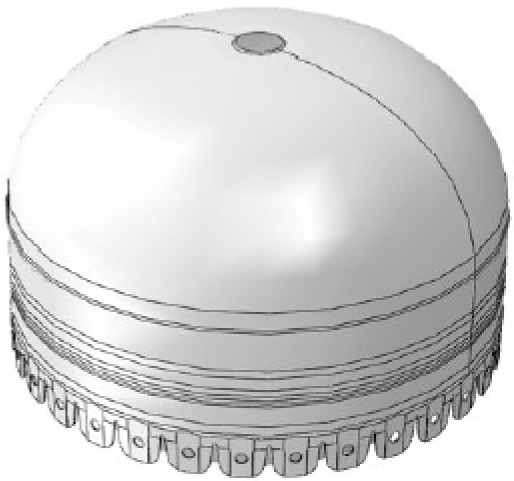
Case Study 2: Satellite Propellant Tank

- COPV tank to be used as a satellite propellant tank, consists of two parts, a vessel and a skirt.
- Only skirt to be looked at, as this study does not focus on COPV
- Skirt manufactured entirely out of composites
- As with the previous case study, the geometry was simplified to avoid meshing difficulties
- All levels of analysis can be applied as long as many simplifications are made to the geometry
- Various load cases applied

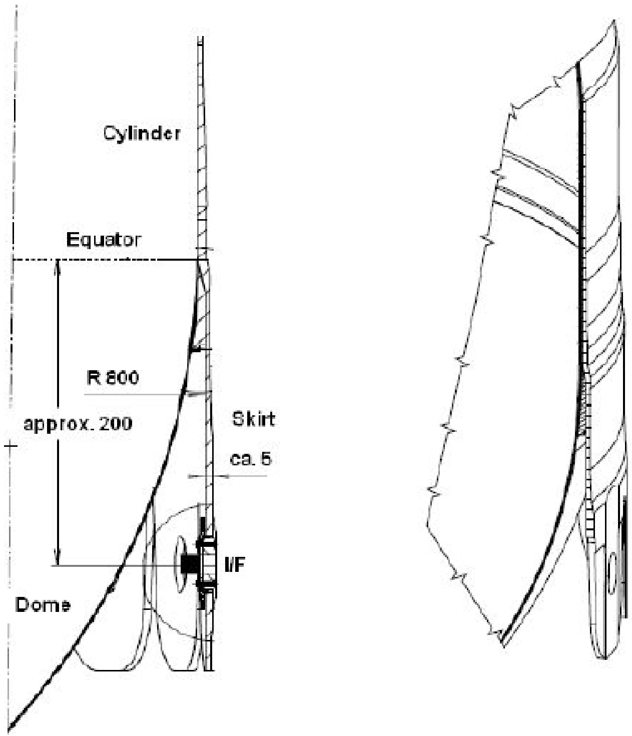
Case Study 2: Satellite Propellant Tank



COPV for use as a satellite propellant tank



General geometry



Geometry of Skirt

Case Study 2: Finite Element Analysis

1. Level 0: performed to identify the critical zones for delamination onset using Ye's criterion.

2. Level 2: Classic VCCT and VCCT Element models using Abaqus.

   Needs a relatively fine mesh to deliver reliable results, excessively coarse mesh causes over-prediction of G values. In order to compute a reliable value of the critical load, a sub-model based approach was performed; this allows a mesh refinement.

Current Status

Next steps

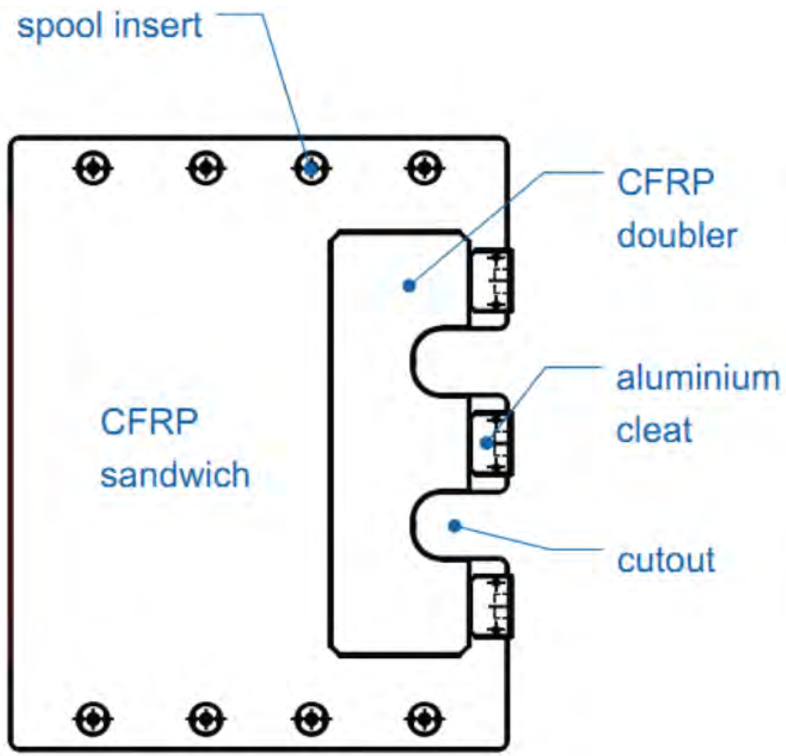
- Implementation of a demonstrator project (manufacturing, test, inspection, …), which is based on the ‘satellite structure’ case study (see next slides)
- The demonstrator structure will be subject to additional analysis, e.g. simple ‘Level 0’ assessments.

Furthermore

- Update the Guidelines documentation with the experiences of the demonstrator project.

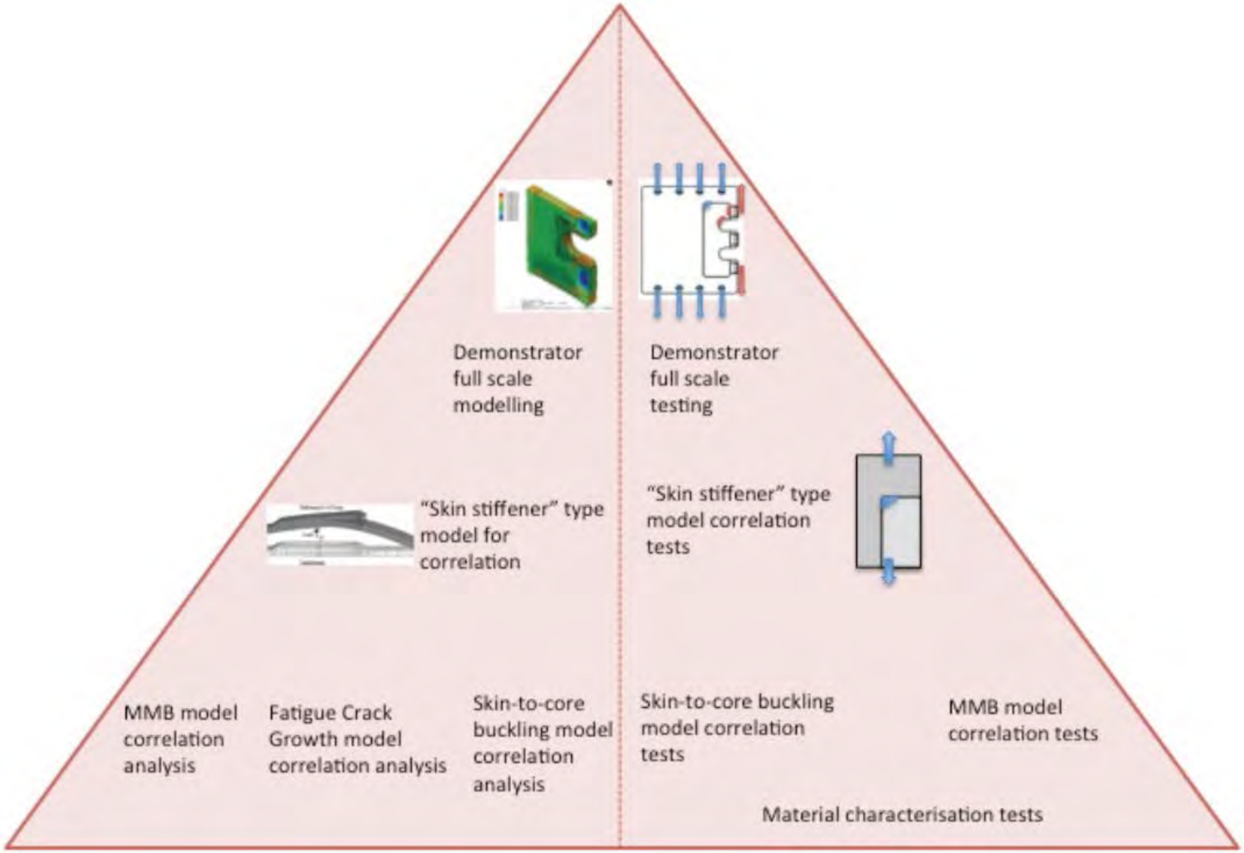
Current Status

- A demonstrator programme is in preparation, focusing on a typical spacecraft structural sandwich panel.



Current Status

– The demonstrator programme will include various ‘building block’ tests (see draft below, for information only).



Future Work

- The initial focus of the activity was not on impact damage.
  We are planning to extend the activity to address more systematically the (potential) effects of impact damage on the demonstrator structure.
- Aspects to be addressed:
    - Specimen design (standardized specimens are probably not suitable for typical spaceflight composite structures)
    - Are analytical approaches possible with reasonable effort? (detailed modeling of impact event? enveloping delamination? enveloping open hole? others?)
    - Determination of ‘damage tolerant (no-growth) threshold strain’, i.e. is there a potential fatigue problem?

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

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References and Links

- ECSS-E-ST-32-01C ‘Fracture Control’ (rev.1, 2009)
  For access to ECSS standards: www.ecss.nl (requires registration)
  Or contact the author.
- Technical Interchange Meeting (TIM) on Fracture Control of Spacecraft, Launchers and their Payloads and Experiments, 23-24 March 2011 (http://www.congrex.nl/10M68/pages/standaard/page_2332.html?pid=2332&page=Programme)
- Workshop on Fracture Control of Spacecraft, Launchers and their Payloads and Experiments, 9-10 February 2009 (http://www.congrex.nl/09c11/programme.asp)
- ‘TN-300 - Damage Tolerance Verification Approach and Best Practice Guidelines’, currently in draft issue.
- ‘TN410 - Best Practice Analysis Methods’ (first issue is available from http://delat.inegi.up.pt/documents.asp)