Considerations for Using Composite Pressure Vessels (CPVs) in Fuel Storage for Automotive Applications

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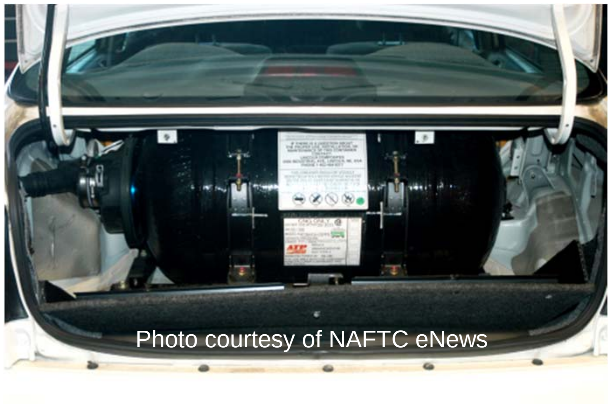
History

- Ongoing initiative to get high energy capacity "green fuel" containers to market quickly and cost effectively
  - The United States has decided to invest in "green energy" technology, to become energy independent, and to "Innovate Our Way to a Clean Energy Future" – (Blueprint for a Secure Energy Future, March 30, 2011, The White House)
- Commercializing NASA-developed high efficiency composite pressure vessel (CPV) fuel storage containers
  - Developed in the 1970s for the Space Shuttle
- U.S. Department of Energy directing rapid commercialization of CPV fuel storage containers with programs like:
  - The ARPA-E Move Program
  - Vehicle Technologies Program
  - Hydrogen and Fuel Cells Program



Composite Pressure Vessel "Green" Fuel Container Installation

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Standards and Regulations

- Initial 15-Year Service Life for Fuel Containers
  - Consensus standard, “ANSI/AGA NGV2-1992, American National Standard for Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers.”
  - Department of Transportation code “Compressed Natural Gas Fuel Containers in 49CFR571.304 Standard No. 304; Compressed Natural Gas Fuel Container Integrity.”
- Growth in CPV fuel container use
  - 9% of world vehicle population by 2020 (65 million vehicles fueled with natural gas)

Photo courtesy of CFS International

Photo courtesy of Show Times

Composite Pressure Vessel
“Green” Fuel Passenger Bus

CPV Type Definitions (TP-304 for FMVSS 304) **Type 2** container is a metallic liner over which an overwrap such as carbon fiber or fiberglass is applied in a hoop wrapped pattern over the liner's cylinder sidewall. **Type 3** container is a metallic liner over which an overwrap such as carbon fiber or fiberglass is applied in a full wrapped pattern over the entire liner, including the domes. **Type 4** container is non-metallic liner over which an overwrap such as carbon fiber or fiberglass is applied in a full wrapped pattern over the entire liner, including the domes.

Issue

- Burst failures of CPV fuel containers during service life
  - 3000-10,000 psi service pressure
    - Kinetic energy pressure release (blast and fragmentation)
    - Possible fire of gaseous contents
  - Potential for injury and loss of life
- Focus: Type 4 CPV fuel container failures
  - 1996 Metro Transit Authority Bus, California-USA
  - 1996 Industrial Accident, Canada
  - 2008 Brisbane Bus, Brisbane-Australia
  - 2009 Delivery Vehicle, California-USA
  - 2012 Brisbane Bus, Brisbane-Australia
  - “Four serious explosion accidents of Type 4 tanks in China” – 12/10/2009 DOE CNG-H2 Workshop

Delivery Vehicle, California 2009 (Type IV)

Passenger Bus, Australia 2009 (Type IV)

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Solution

- NHTSA call to work with NASA and NIST to investigate failures (IAA DTNH22-10-X-00259)
  - Minimize risk of failures in “green” fuel vehicle gas tanks
- Program Objectives
  1. Perform unbiased investigations to determine root cause(s) of failures
     - Review failures of CPV fuel containers in the U.S.
     - Review failures in other countries that have implemented broad use of CNG vehicles and where cylinder type and root cause(s) are not explained or are unknown
  2. Determine if current codes and standards ensure public safety for CPV fuel containers
  3. Fill holes in codes and standards through conduct of development test and evaluation activities

Program Overview

- The initial focus is on testing and evaluation of Type 4 cylinders that are:
  - 1. Failed, 2. Unfailed and removed from service (Pasedna-CA case study), and 3. Certified new
- Program is a three-phased process - not fully funded
  - Phase I - Establish internal and external condition of CPV fuel tanks after service, generic Type 4 fault tree analysis (FTA)/failure investigation (FI) methodology, and nondestructive testing per WSTF-TP-1178-001-11.
  - Phase II - Vessel sectioning, destructive testing, fault tree validation, design of experiments, materials analysis, and mechanical properties per WSTF-TP-1178-002-12.
  - Phase III - Burst testing, durability testing, analyzing results, and final reporting of data.

Program is reviewed by agency integration team (Includes NASA, DOT-NHTSA, DOT-PHMSA, DOE, FAA, and NIST) and is under an interagency technical core team

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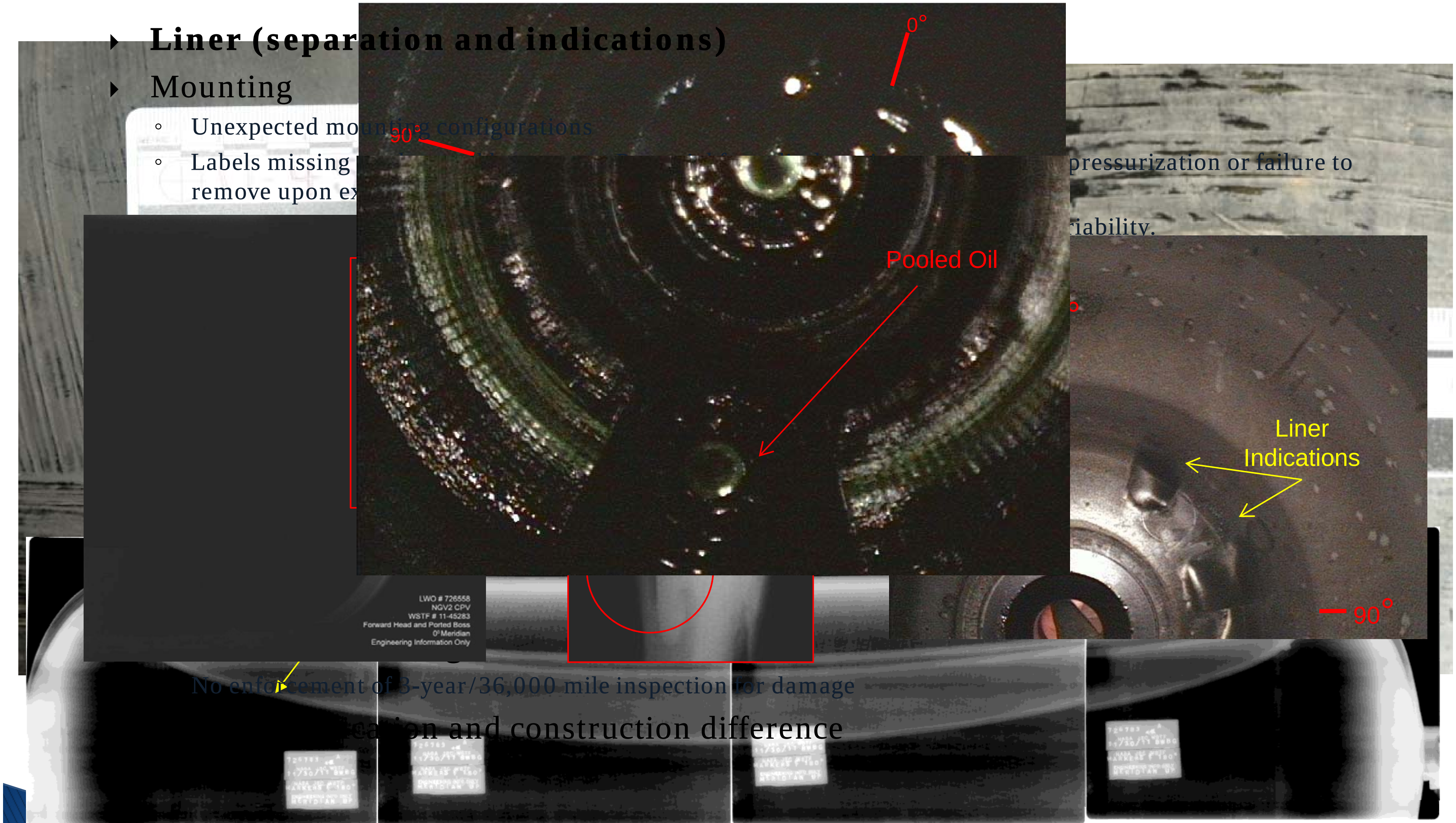
Phase I Nondestructive Service Evaluation Results

- **Liner (separation and indications)**
- Mounting
  - Unexpected mounting configurations
  - Labels missing
    remove upon ex
  - pressurization or failure to
  - iability.
  - No enforcement of 3-year/36,000 mile inspection for damage
- ca ion and construction difference



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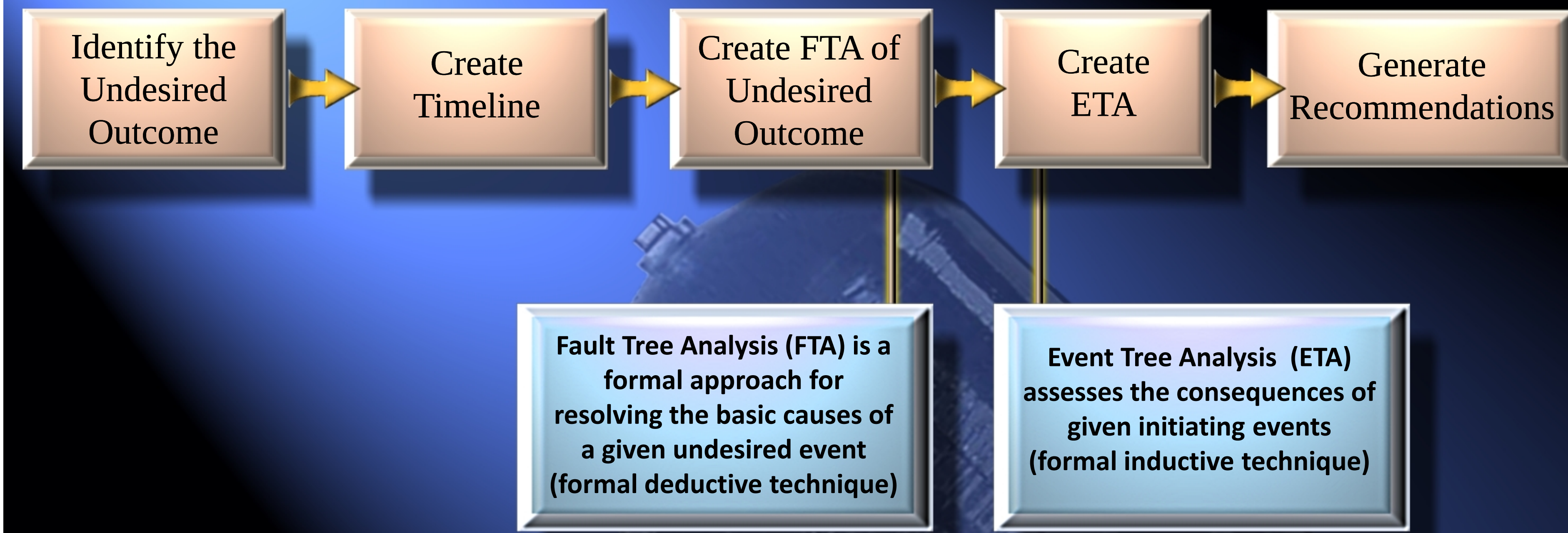
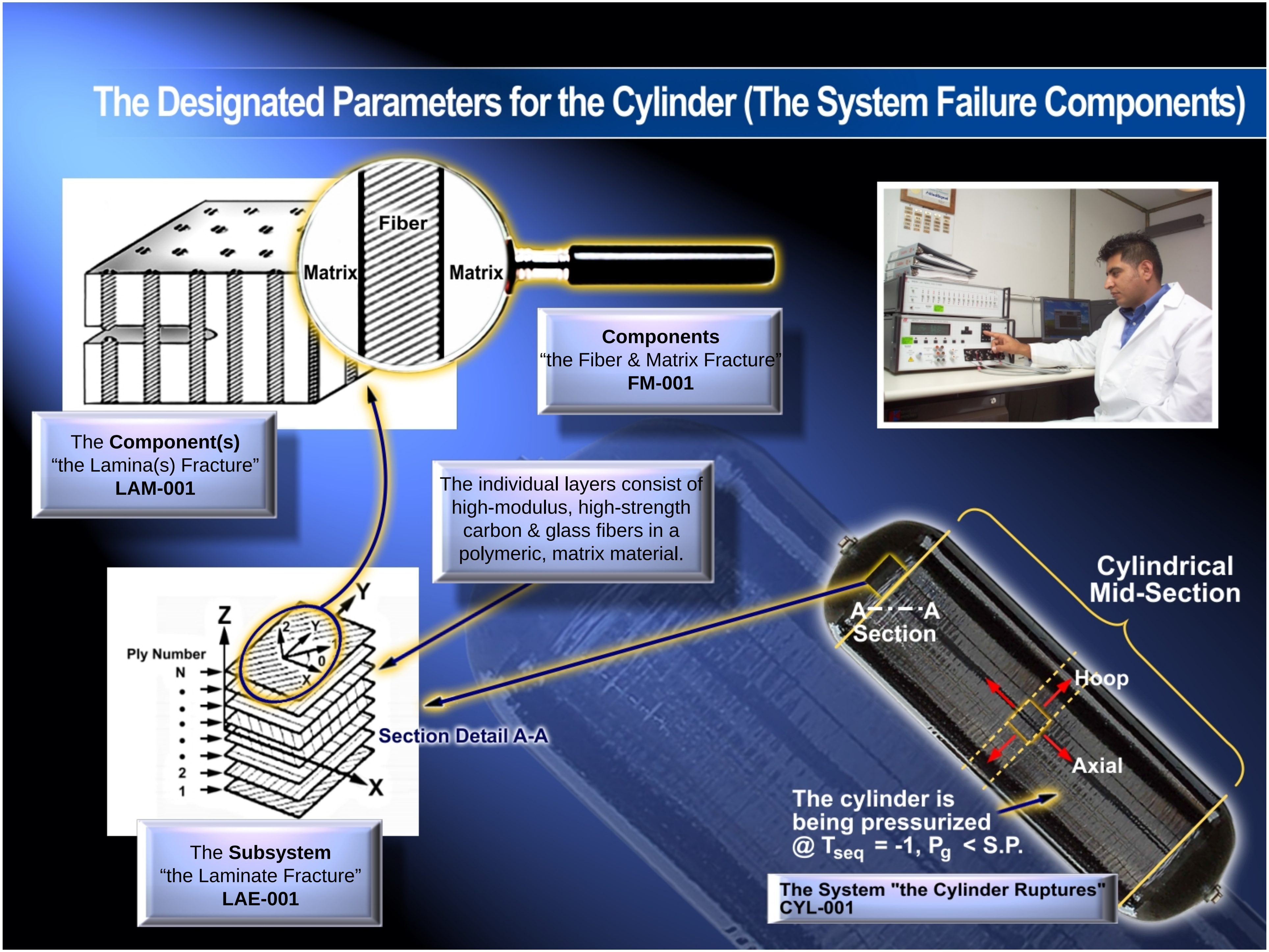
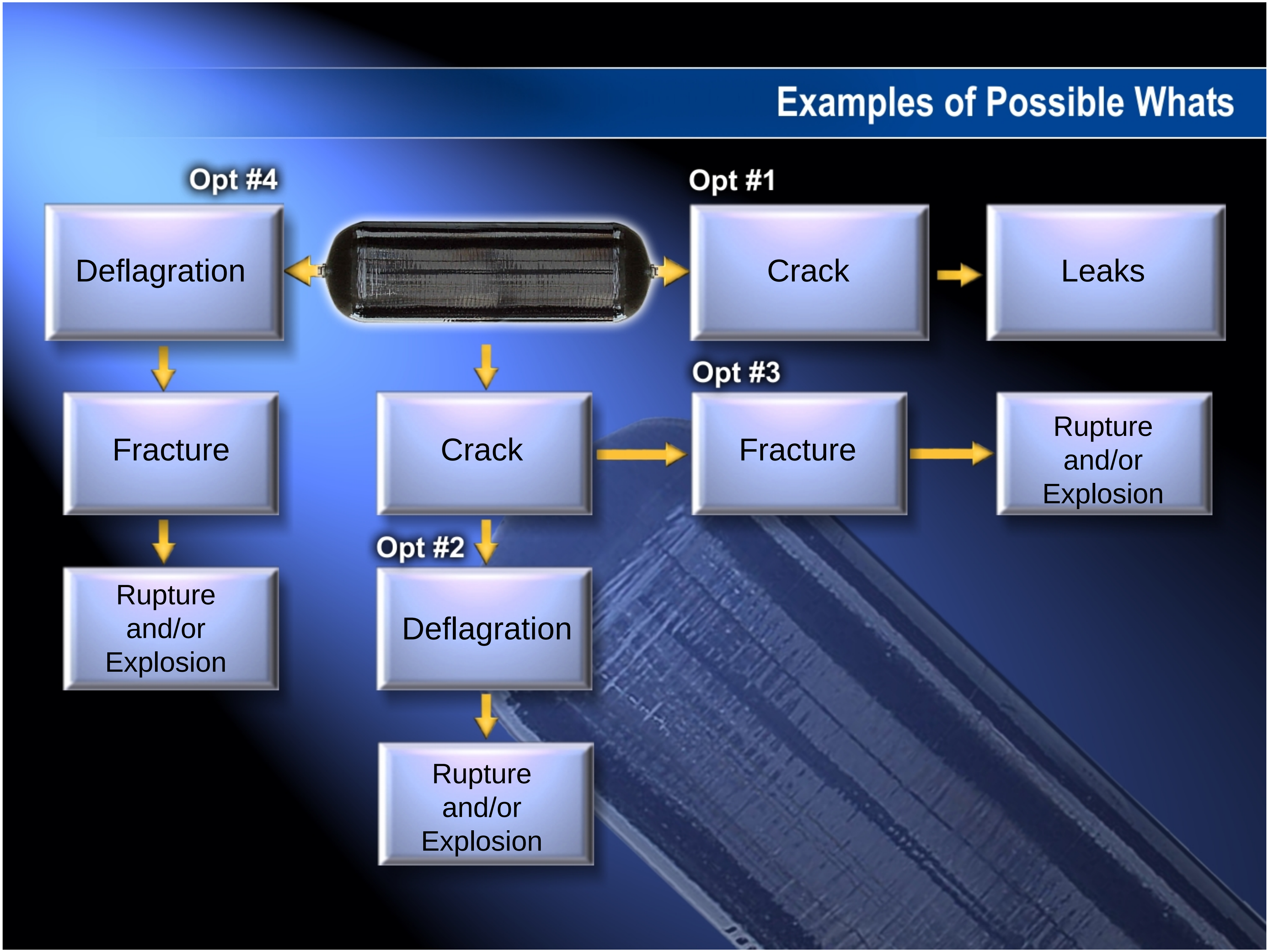
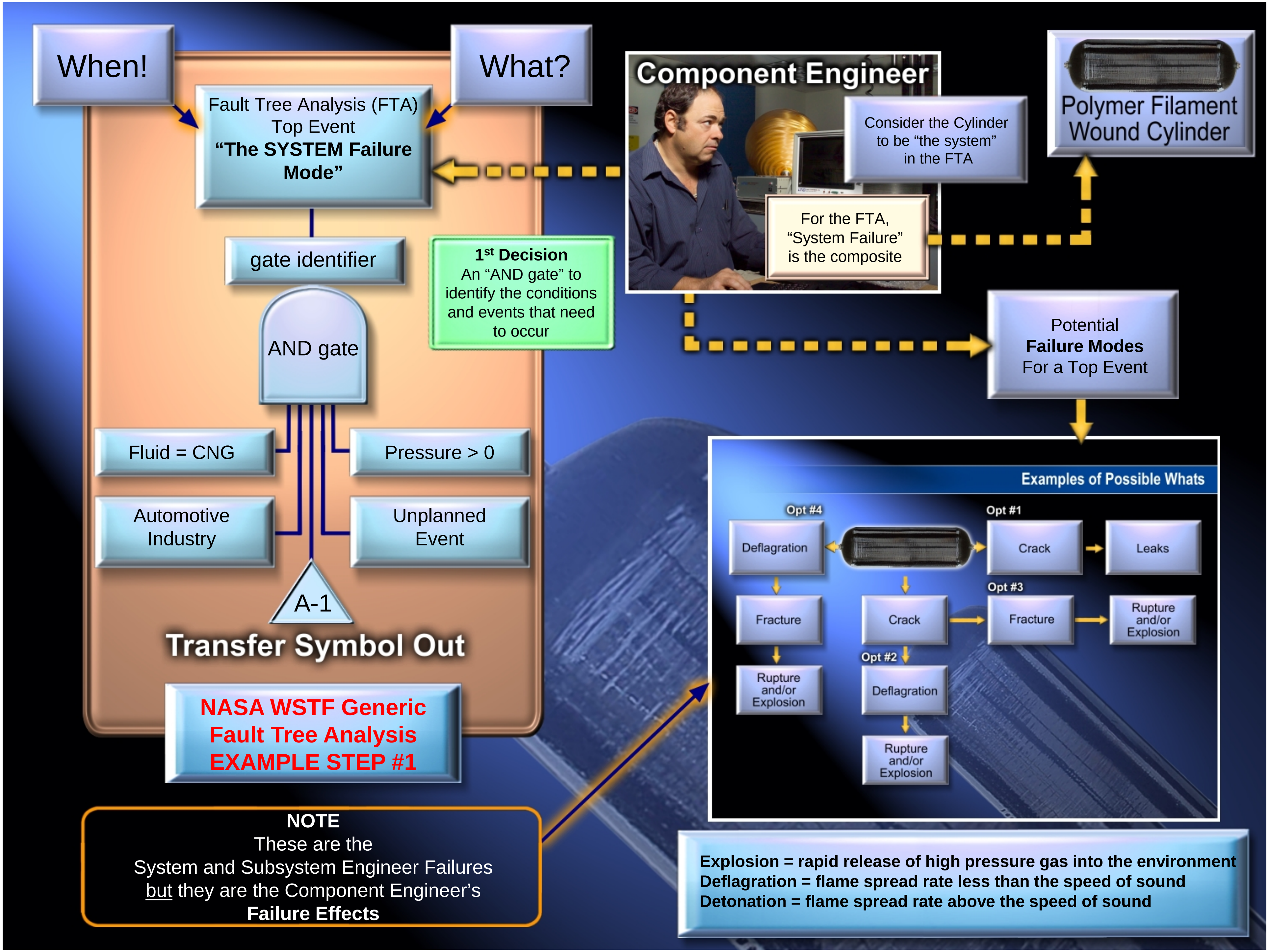
Typical NASA Root Cause Analysis (RCA) Method




The Designated Parameters for the Cylinder (The System Failure Components)
Fiber
Matrix
Matrix
Components
“the Fiber & Matrix Fracture”
FM-001
The Component(s)
“the Lamina(s) Fracture”
LAM-001
The individual layers consist of high-modulus, high-strength carbon & glass fibers in a polymeric, matrix material.
Ply Number
N
2
1
Z
Y
X
Section Detail A-A
The Subsystem
“the Laminate Fracture”
LAE-001
Cylindrical Mid-Section
A — · — A Section
Hoop
Axial
The cylinder is being pressurized @ T_{seq} = -1, P_g < S.P.
The System "the Cylinder Ruptures"
CYL-001


Examples of Possible Whats
Opt #4
Deflagration
Opt #1
Crack
Leaks
Fracture
Crack
Opt #3
Fracture
Rupture and/or Explosion
Rupture and/or Explosion
Opt #2
Deflagration
Rupture and/or Explosion


When!
What?
Fault Tree Analysis (FTA)
Top Event
"The SYSTEM Failure Mode"
gate identifier
AND gate
1st Decision
An "AND gate" to identify the conditions and events that need to occur
Fluid = CNG
Pressure > 0
Automotive Industry
Unplanned Event
A-1
Transfer Symbol Out
NASA WSTF Generic
Fault Tree Analysis
EXAMPLE STEP #1
NOTE
These are the
System and Subsystem Engineer Failures
but they are the Component Engineer's
Failure Effects
Component Engineer
Consider the Cylinder to be "the system" in the FTA
For the FTA, "System Failure" is the composite
Polymer Filament Wound Cylinder
Potential
Failure Modes
For a Top Event
Examples of Possible Whats
Opt #4
Deflagration
Fracture
Rupture and/or Explosion
Opt #1
Crack
Leaks
Crack
Opt #3
Fracture
Rupture and/or Explosion
Opt #2
Deflagration
Rupture and/or Explosion
Explosion = rapid release of high pressure gas into the environment
Deflagration = flame spread rate less than the speed of sound
Detonation = flame spread rate above the speed of sound

Phase II Destructive Evaluation Results

- Validated sectioning on new pathfinder vessel
- Cross-sectioning CPV fuel containers removed from service (in process)
- Physical and chemical properties on new CPV fuel containers and CPV fuel containers removed from service (in process)
- Validate generic fault tree analysis (FTA)/FI methodology against Type 4 case studies

NASA White Sands Test Facility Personnel Cross-sectioning a CPV Fuel Container

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Phase II Validation of Generic FTA/FI Methodology Results

- Inputs to fault tree analysis/generic FI methodology from review of all Type 4 failures
  - Known failures are during the 15-year service life
  - Burst failure mode observed (the technical community expects leakage)
  - Head-to-dome transition failure observed (the technical community expects predictable side wall leakage)
- Inputs from documented case study
  - Two vessels burst
  - Vertical vessel support ring damage
  - Fracture pattern in the fiber and liner
- FTA indicates failure initiated in CPV tank head-to-dome transition

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Phase III Burst and Durability Testing

- Residual life determination
  - Cycling Testing
    - DOE provided new CPV fuel containers and 15,000 cycle testing that complimentary meets some of NHTSA's test matrix
  - Pneumatic Burst Testing
    - Failure mode testing on at least one CPV fuel container removed from service
- Closure of fault trees for case study failures
  - Narrow the CPV fuel container FTA from generic to specific using the Pasadena California case study
- Determination of probable failure mechanism(s)
- Data for updating codes and standards
- Report

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Summary

- Type 4 cylinder service evaluation is complete
- Cross-sectioning completed on a new Type 4 CPV fuel container
- Cross-sectioning of vessels removed from service in process
- Validation of the generic Type 4 FTA/FI methodology in process
- Developing the Phase III Burst and Durability Test Plan
- Initiate burst and durability testing in FY13
- Update codes and standards with new knowledge
- Generic FTA/FI investigation validation for Type 2 and Type 3 cylinders not currently funded
- Repeating for Type 2 and Type 3 cylinders not funded

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Thank you

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http://www.nasa.gov/centers/wstf/laboratories/composite/index.html

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- The International Association of Natural Gas Vehicles (IANGV, Auckland, New Zealand)

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