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

Nathanael Greene, NASA White Sands Test Facility
Darren Cone, NASA White Sands Test Facility
Harold Beeson, PhD., NASA White Sands Test Facility
David McCloskey, National Institute of Standards and Technology
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
Standards and Regulations

- Initial 15-Year Service Life for 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)

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)
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.
Phase I Nondestructive Service Evaluation Results

- **Liner (separation and indications)**
  - Mounting
    - Unexpected mounting configurations
    - Labels missing or obscured by mounts. Potential for cylinder misuse such as over pressurization or failure to remove upon expiration.
    - A variation in geometry, that could lead to potential strength and/or mounting variability.
  - Interfacing connections
    - Unexpected variation in fitting break-away torque from below 5 ft-lb to 170 ft-lb. No provision for proper fitting torque application (leakage at the fitting) could result in flammability and hypoxia hazard inside and outside of vehicles. Over torque could result in damage to the CPV fuel container.
  - Durability issues
    - Labels did not “remain in place and be legible for the manufacturer’s recommended service life” per the FMVSS 304 section S7.4 requirement
    - Limited shipping protection (exposure to chemical and mechanical damage)
  - Media compatibility/chemical damage
    - Interior liquid pooling
  - Mechanical damage
    - No enforcement of 3-year/36,000 mile inspection for damage detection and construction difference
Typical NASA Root Cause Analysis (RCA) Method

1. Identify the Undesired Outcome
2. Create Timeline
3. Create FTA of Undesired Outcome
4. Create ETA
5. Generate Recommendations

Fault Tree Analysis (FTA) is a formal approach for resolving the basic causes of a given undesired event (formal deductive technique).

Event Tree Analysis (ETA) assesses the consequences of given initiating events (formal inductive technique).
The Designated Parameters for the Cylinder (The System Failure Components)

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.

The Subsystem
"the Laminate Fracture"
LAE-001

The System "the Cylinder Ruptures"
CYL-001

The cylinder is being pressurized @ $T_{seq} = -1, P_g < S.P.$

Cylindrical Mid-Section

Section Detail A-A

A Section
Examples of Possible WHATS

Opt #4

Deflagration

Fracture

Rupture and/or Explosion

Opt #1

Crack

Leaks

Opt #3

Crack

Fracture

Rupture and/or Explosion

Opt #2

Deflagration

Rupture and/or Explosion
Fault Tree Analysis (FTA)

Top Event

“The SYSTEM Failure Mode”

1st Decision
An “AND gate” to identify the conditions and events that need to occur

AND gate

Fluid = CNG
Pressure > 0
Automotive Industry
Unplanned Event

A-1

Transfer Symbol Out

NOTE
These are the System and Subsystem Engineer Failures but they are the Component Engineer’s Failure Effects

NASA WSTF Generic Fault Tree Analysis EXAMPLE STEP #1

Component Engineer

Consider the Cylinder to be “the system” in the FTA

For the FTA, “System Failure” is the composite

Potential Failure Modes For a Top Event

Examples of Possible Whats

Opt #1
Crack
Leaks

Opt #2
Fracture
Rupture and/or Explosion

Opt #3
Rupture and/or Explosion

Deflagration

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
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
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
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
References

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- http://push.pickensplan.com/photo/photo/show?id=2187034%3APhoto%3A225586&context=album&albumId=2187034%3AAlbum%3A447634
- The International Association of Natural Gas Vehicles (IANGV, Auckland, New Zealand)