Needed R&D for improving carbon composite cylinders design requirements

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Thesis : current standards for carbon composite vessels can be improved

- **Were developed considering mostly degradation mechanisms seen in other materials than carbon composites**
  (e.g. stress rupture of fibers by stress corrosion)

- **Not fully *performance based* :**
  “arbitrarily” defined safety margins which may be overly conservative

Various types of use of carbon composite cylinders need to be considered

AIR LIQUIDE

- **Permanently mounted vehicle fuel tank, subject to fast fuelling**
  - ISO/DIS 15869
- **Cylinders for the transport of hydrogen**
  - ISO/IS 11119-3 and Pr EN 12245
- **Stationary storage**
  - No standard yet

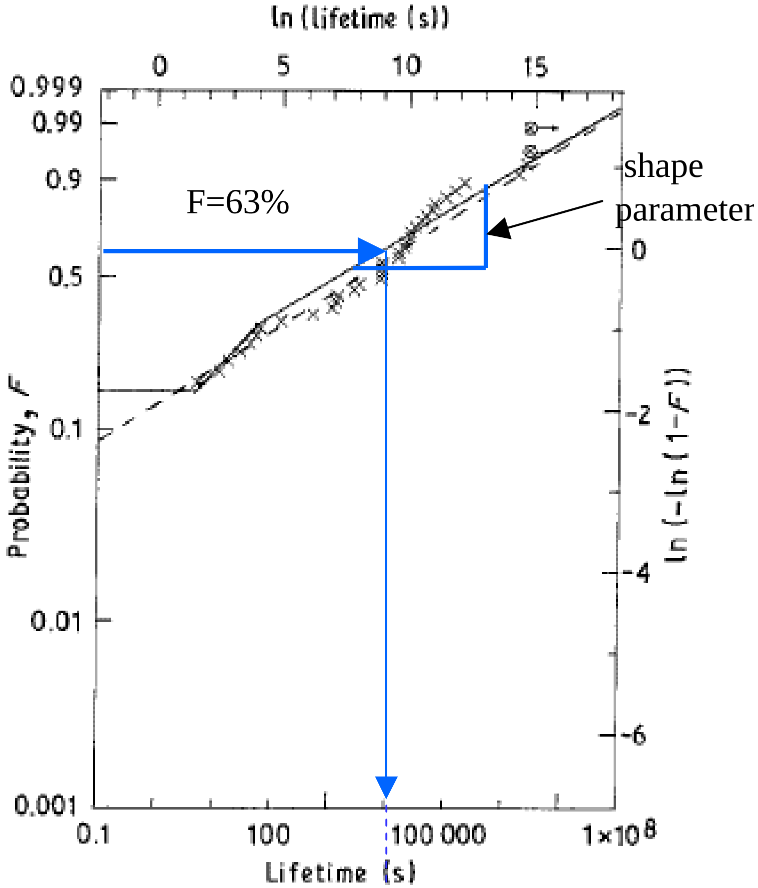
Basis for current burst pressure (BP) ratios (1)

AIR LIQUIDE

- **Feared failure mechanism : Stress Rupture of composite**
  - Stress rupture : Failure under constant load (creep rupture)
- **Data : stress rupture tests on strands**
  - Strand : fiber (a few to thousands filaments), resin coated and cured
  - Stress rupture test : strands held under constant tensile stress until rupture (up to 10 years)

Strand stress rupture test

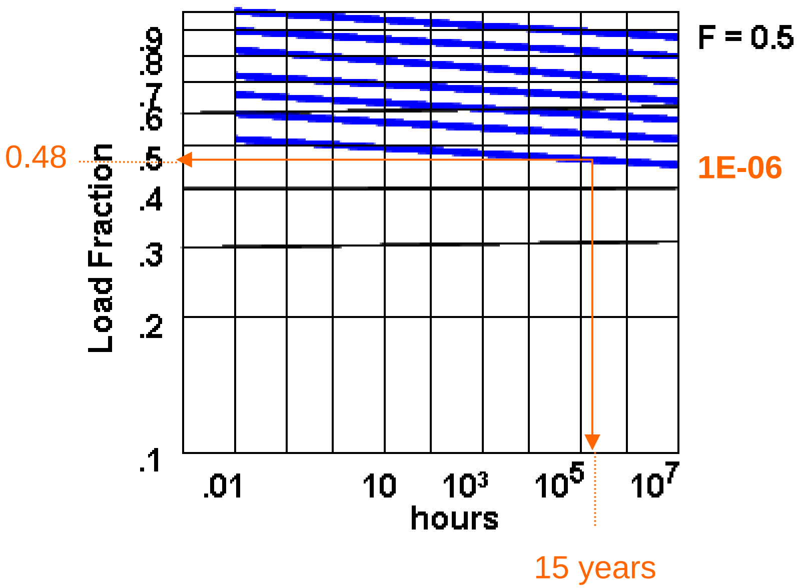
7 fiber strands loaded at 88% of



Weibull scale parameter

Source :Otani, H., S.L. Phoenix, and P. Petrina, Matrix effects on lifetime statistics for carbon fibre-epoxy microcomposites in creep rupture. Journal of Materials Science, 1991. 26: p. 1955-1970.

Basis for current burst pressure ratios (2)



To have a probability of failure after 15 years less than 1e-6

Constant load must not exceed : 0,48 x initial average strength

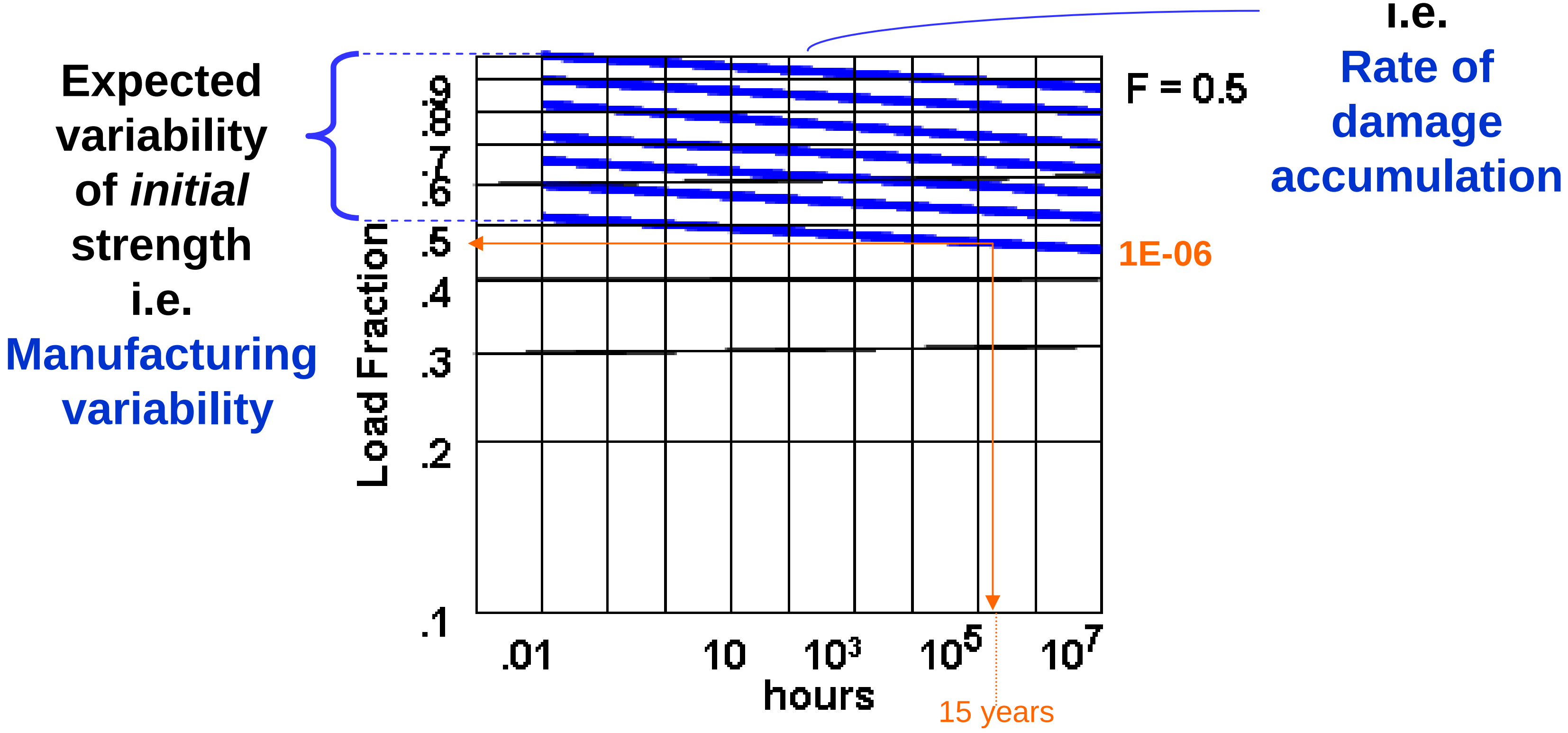
→ BP ratio requirement :
BP/NWP > 1/0,48= 2,08 (→ 2,25)

Ref : Shaffer, J.T. Stress Rupture of Carbon Fiber Composite Materials. in 18th International SAMPE Technical Conference Proceedings. 1986. Seattle, WA.

Note : “Load fraction” is in reference to average burst pressure, not minimum specified burst pressure.

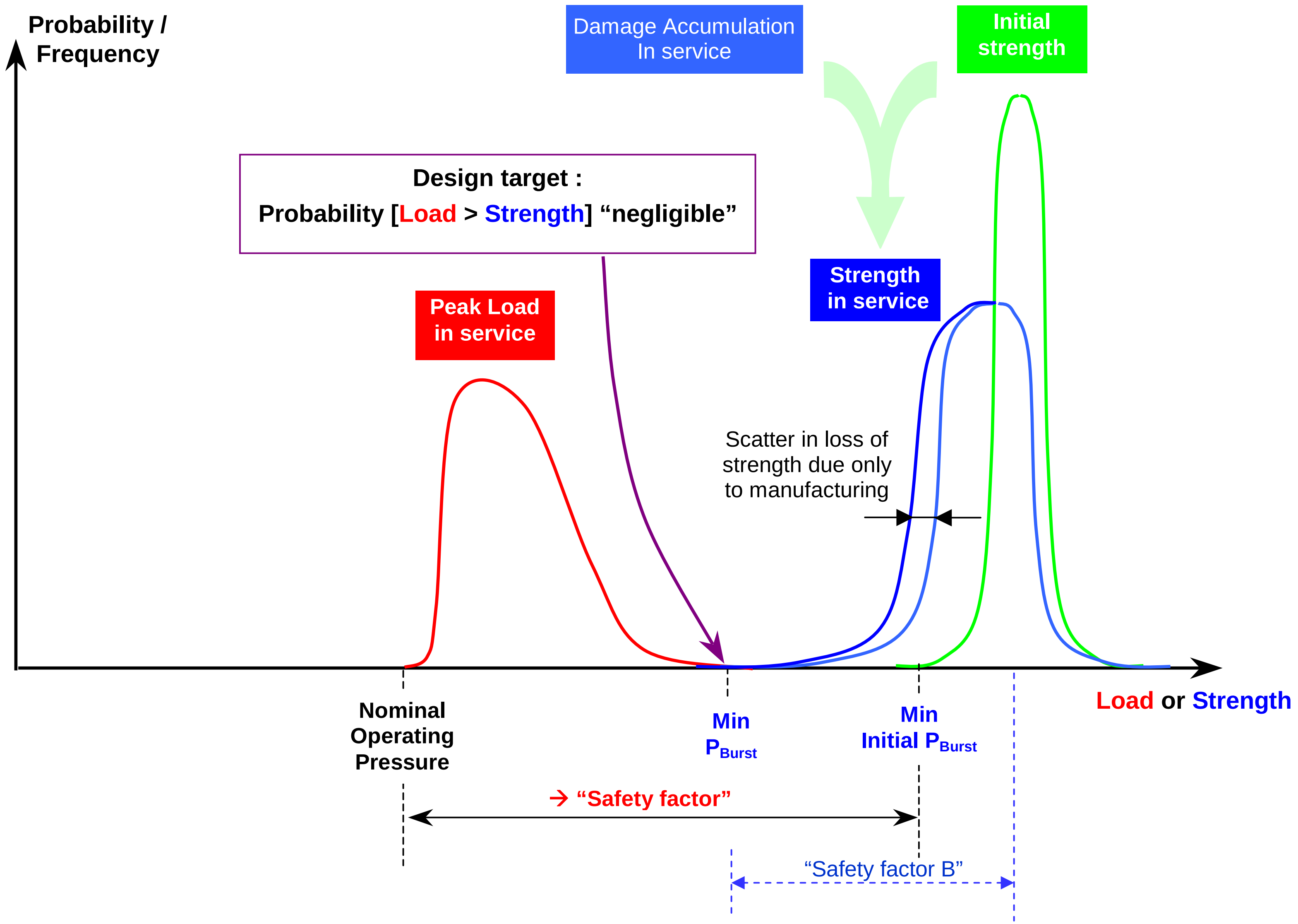
Two key parameters impact BP ratio requirement

- Variability of initial strength
- Potential loss of strength over time



Note : Above load fraction is in reference to average burst pressure, not minimum specified burst pressure

General principle for determining performance based design requirements



There are sources of inaccuracy to be addressed

NEEDED BASIS

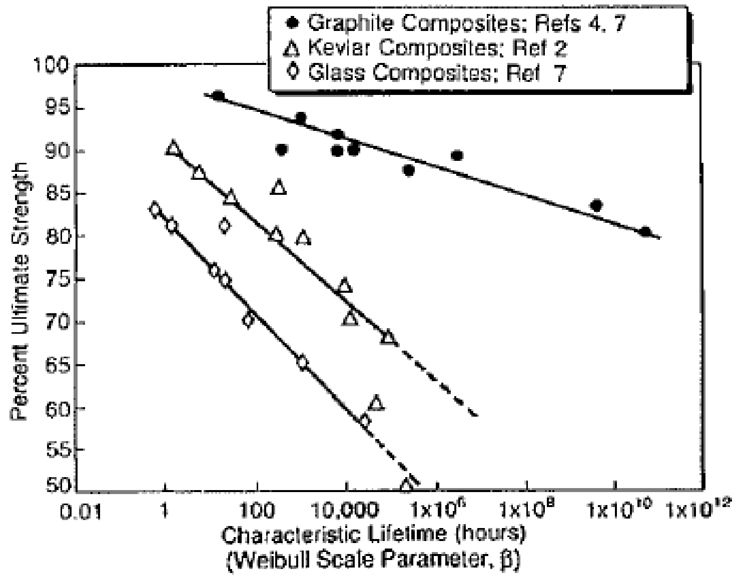
- **Current materials**
- **Cylinder behavior**
- **All types of load (cyclic, ...)**
- **Behavior at different temperatures and environmental conditions**
- **All failure modes**

  incl. liner failure and wrapping delamination

Nature of the damage accumulation is understood

- **Glass fiber composite**
  - The glass fiber itself is subject to stress rupture due to stress corrosion, resulting in a loss of strength of the composite over time
- **Carbon composite**
  - Carbon fiber is NOT subject to stress rupture, nor fatigue
  - Damage accumulation results from relaxation of the matrix, producing further failures around single fiber breaks

→ Driving mechanism is visco-elastic behavior of matrix



Ref :Babel, H.W., B.D. Vickers, and D.A. Thomas, AIAA 89-2644 Sustained Load Behavior of Graphite/Epoxy Metal-Lined Pressure Vessels for Long-Life Space Applications, in AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference. 1989: Monterey, CA USA.

Need to fully understand the impact of the changes occurring in the carbon composite wrapping

- **How can damage accumulation be quantified and measured ?**

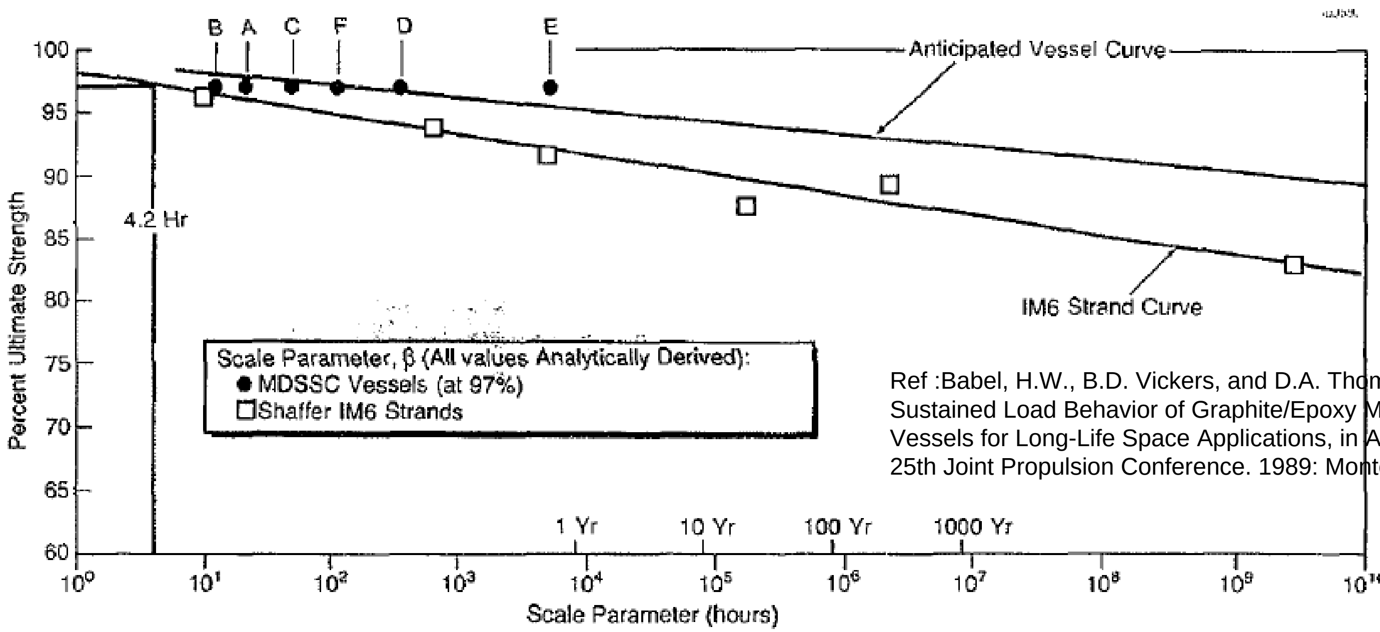
- **How can damage accumulation occur in normal service ? At what rate ?**
  - Association of cyclic and static loads
  - Repeated shock
  - Impact of cylinder structure (winding pattern ; wall thickness...)

- **How do service conditions impact rate of degradation ?**
  - Temperature
  - Other condition affecting matrix properties (humidity, ...)

- **In what conditions can redistribution of stresses produce liner failure (type 3) and delaminating (type 4)**

Data on cylinder behavior is very scarce

- Need of conclusive data for vessels at stress levels found in actual service (50%-60%)
- Need to know what conclusions can be drawn for cylinder from strand properties



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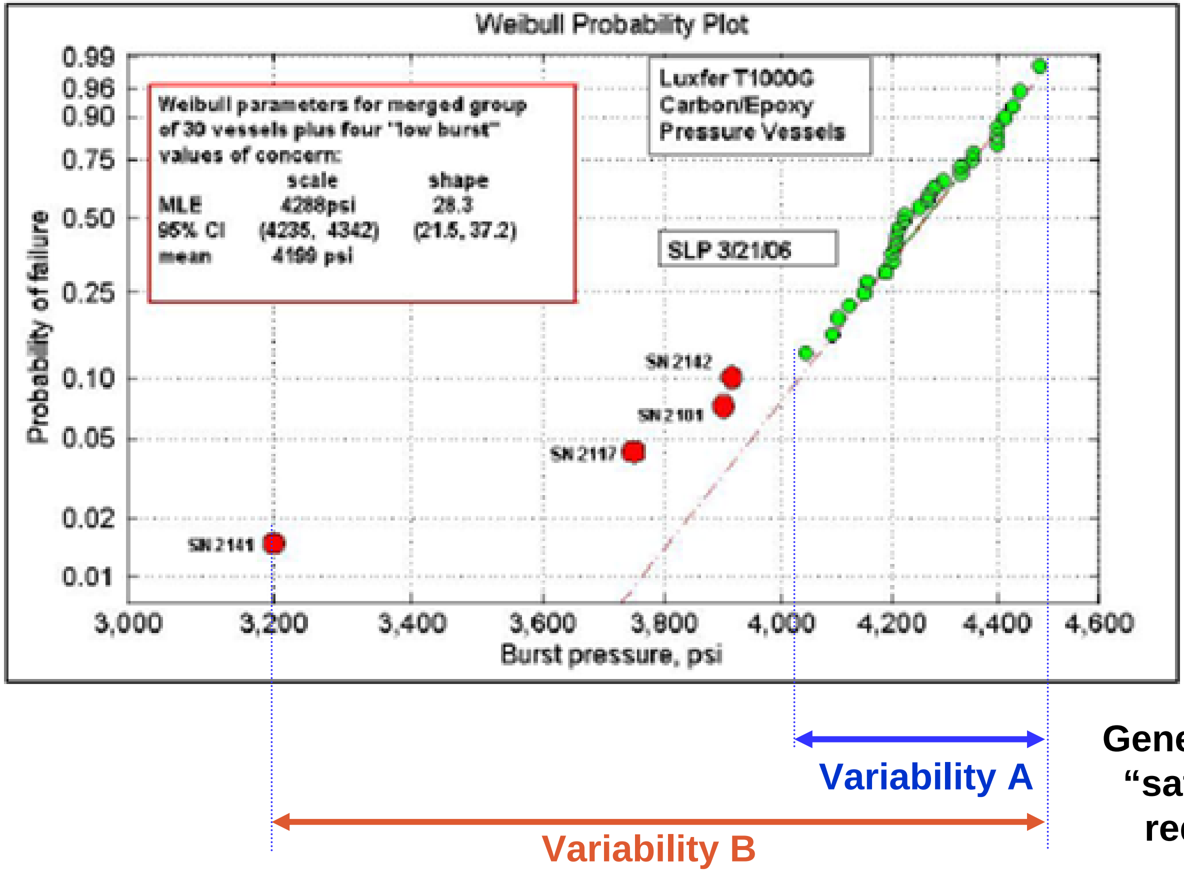
Note : Kevlar fiber vessels show this trend also.

Parameters determining manufacturing variability need to be under control

- **Manufacturing variability directly impacts required “safety margin”**



Generate different “safety margin” requirements

Source :Grimes-Ledesma et al. "Testing of Carbon Fiber Composite Overwrapped Pressure Vessel: Stress Rupture Lifetime.” 2006.

Summing-up, a new knowledge base is needed for defining testing requirements that are truly "performance based"

- BP requirement directly based on possible loss of strength (for anticipated service conditions) and controlled manufacturing variability
- "Accelerated test" conditions producing the same effects as the anticipated service conditions over service life
- Endurance requirements based on actual anticipated service life and controlled manufacturing variability

Note :

- Strategy to adopt with regards to accidental situations (fire, severe impact...) depends on the application.
- Means of protection to be built into design should be determined separately.

- Manufacturing control and production testing requirements demonstrating achievement of the expected performance for all cylinders

In complement to design and manufacturing tests :

- In service inspection test to verify/demonstrate continued fitness for service

Conclusion

- High pressure storage of hydrogen is a central and critical function in all applications.
- For ensuring a maximum level of safety while avoiding over-design, design requirements need to consider the actual behavior of the material and be performance based in essence.
- RCS focused applied R&D on carbon composite cylinders is needed to generate the knowledge base that is required to have performance based design requirements.

Thank you

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