



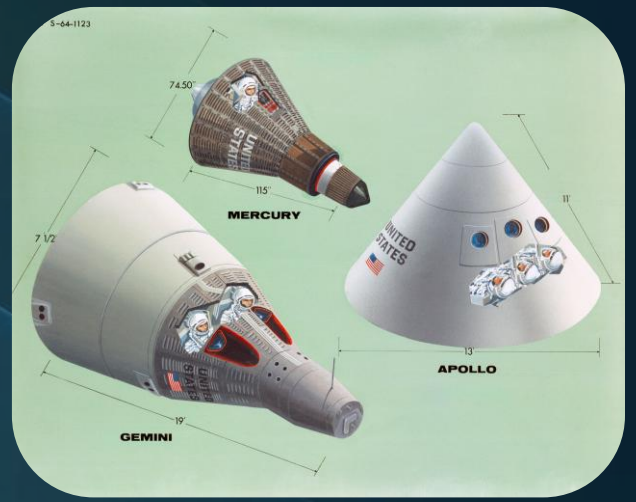

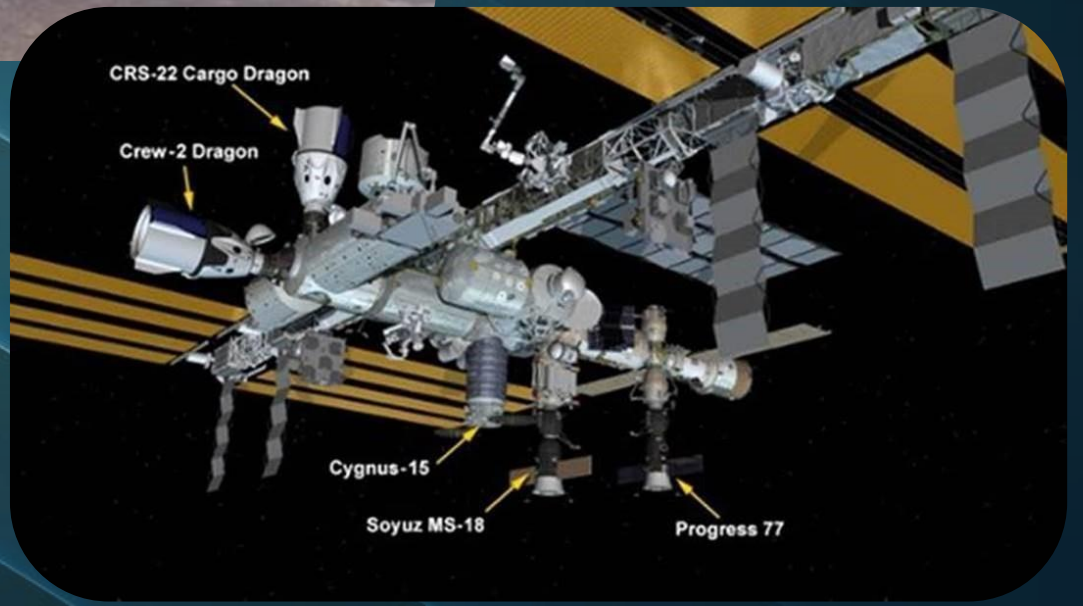

Fracture Control and Damage Tolerance Lifing Challenges at NASA

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Nobody wants hardware failure!

- Transportation, automotive, rail, oil & gas, medical, etc
  - Consequences include human safety, equipment, environmental, etc
- NASA policy: produce flight systems with a high degree of reliability and safety
  - Sound engineering practices in design, analysis, inspections, testing, fabrication, maintenance, operations
  - Design for redundancy where possible
  - Design for minimum risk
  - Design and Construction standards (such as NASA-STD-5019, *Fracture Control*)

NASA Fracture Control

- Specialized philosophy to address consequences of naturally-occurring and service-induced damage
  - Required for human-rated hardware; optional for robotic
  - All phases of life: manufacture, test, transportation, service, refurbishment for re-use

- Involves understanding of
  - Hardware design and usage
  - Materials and processes (additive manufacturing, welding, forging, heat treatment)
  - Load spectrum (static, dynamic, cyclic) and stress state (tensile, bending, shear)
  - Environment (temperature, corrosive fluids)
  - Fracture mechanics and non-destructive evaluation (NDE)

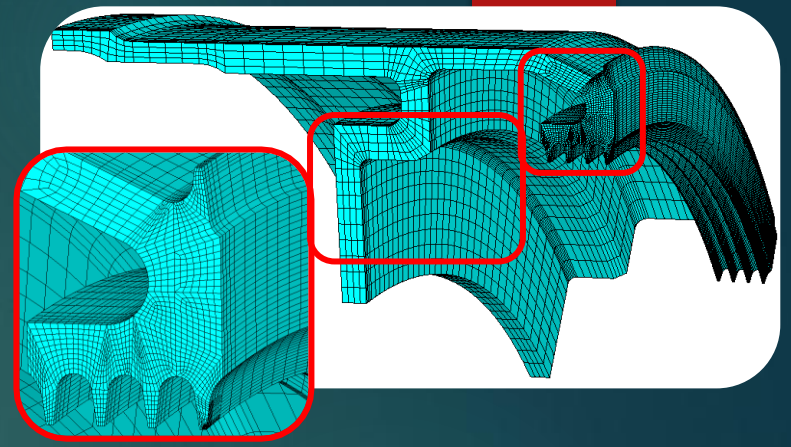
General Fracture Control strategy

- Part classification according to consequence of failure
  - Fracture critical (failure = bad day for all)
  - Non-fracture critical (failure = performance reduction)
  - Exempt (small mass-produced parts, or non-structural parts)
- If Fracture critical: flaw screening, damage tolerance to 4x service life
- Documentation of fracture control activities (plan, summary)
- Disposition of non-conformances and detected flaws
- Fracture Control applies equally to
  - In-house hardware
  - Contractor-provided hardware
  - Commercial-off-the-shelf (COTS) hardware

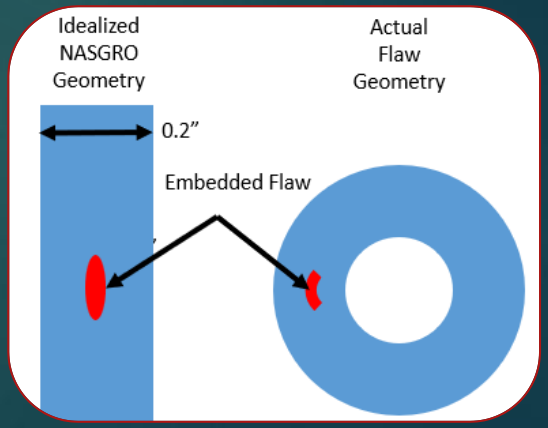
Damage tolerance analysis and/or test

- Going to focus on aspects of fracture critical parts herein
- Damage tolerance analysis or test must be to 4x service life
  - Initial flaw size given by flaw screening method: typically NDE but can be by proof test
  - 4x life factor to conservatively bound crack sizes, applied stresses, material properties
- Analysis is almost always deterministic
  - With low flight counts (certainly relative to aviation), not enough data on input variability for probabilistic analysis
  - Certainly a very conservative, binary approach (fail/no fail)
- Testing is always deterministic
  - Fracture behavior has significant scatter
  - Testing in sufficient volume to bound input variability for probabilistic assessment is not feasible
- If linear elastic material behavior, then either analysis or test, otherwise test only

Challenges - basic



- Insufficient NDE access
  - Example: post-proof test NDE for welds in pressurized parts
- Insufficient fracture material data, property variability, multiple materials, etc
  - Examples: welds vs parent material, temperature/environment, etc
  - Use bounding data or knockdown factors
- Complex part geometry/loading may not fit well with predefined analytical models
  - Examples: embedded curved flaws in cylindrical walls, unique stress gradients, continuing damage (stiffeners/web), local yielding, etc
  - Use bounding analytical models, bounding stress distributions, examine stress gradients for qualitative assessments
  - Best case: assessment is overconservative, sacrificing performance
- Must assess risk level of the assumptions



Challenges - advanced

- *It's all about the mass …* savings: new space structures increasingly consider use of
  - Composite materials: liner-less pressure vessels, primary structure
  - Polymers: window pressure panes, liner-less pressure vessels, lunar rover tires, pressurized containers
  - Additive manufacturing (AM): primary structure, pressure vessels, lunar rover tires
  - Shape-memory metallics: lunar rover tires
- Results in new challenges to inspection and damage tolerance demonstration
  - Metallics K-based approach may not work due to LEFM limitations (anisotropy, visco-elastic/plastic, etc)
  - Damage propagation and failure modes differ from metallics
  - Traditional NDE struggles due to issues like density variations and material response
  - Often testing with intentionally inserted damage is the only way
- Updating Fracture requirements to meet these challenges is ongoing and evolutionary
  - Fundamental tenet remains: provide acceptable evidence that the hardware can execute its function within its service life without failure

Additive manufacturing (AM)

- AM offers design flexibility to enable previously impractical or impossible designs that cannot be replicated by traditional subtractive processes
  - Typical use case is small quantities of complex components
- AM components with complex geometries, integral internal features, and unimproved surfaces challenge traditional NDE techniques
  - Rough, as-built surfaces trap penetrant fluid, leading to reduced detection reliability
  - Complex geometries limit access to Eddy Current and Ultrasonic inspections
  - Part complexity and material density challenge X-ray penetration and image interpretation
- AM material quality is highly process sensitive
  - Inherently prone to flaws that vary strongly with process refinement and user experience
  - Quality & performance assumptions cannot be transferred across AM techniques, vendors, or systems
- This challenges foundational assumptions that support the use of analysis- or test-based rationale for demonstrating damage tolerance
  - Components are produced from quality materials controlled by aerospace specifications
  - Relevant material properties are well characterized or conservatively bounded
  - NDE inspections are reliable and have appropriate detection capabilities

Additive manufacturing, cont'd

- AM challenges the foundational assumptions
  - Components are produced from quality materials controlled by aerospace specifications
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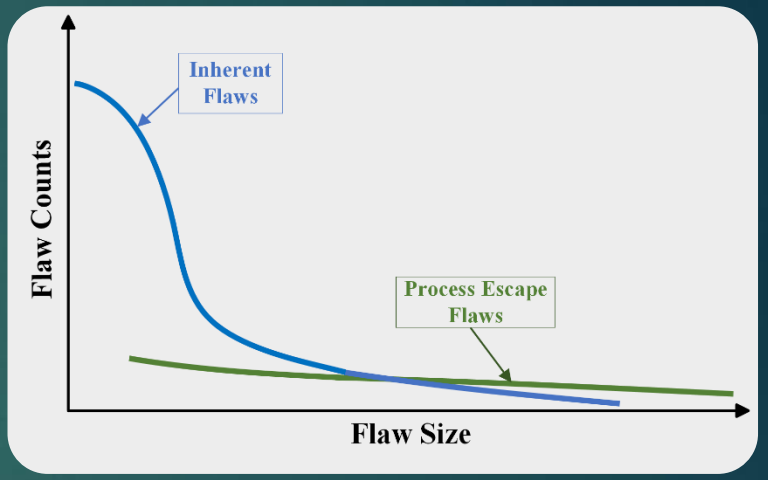
  - NDE inspections are reliable and have appropriate detection capabilities
- Necessitates additional process development and control
- Necessitates advanced inspection techniques
  - In-situ sensors, CT scanning … not yet at required detection reliability
  - NASA requires 90% detection probability with 95% confidence level
    - "90/95 POD"
- Probabilistic assessment may be more appropriate
  - Requires statistical knowledge of inherent flaw and process escape flaw distributions
    - Process escape flaw example: delamination
    - Inherent flaw example: small gas entrapped porosity
    - Inherent flaws could also be associated with process escapes
  - Multiple scenarios then assessed relative to Critical Initial Flaw Size (CIFS) and inspectability



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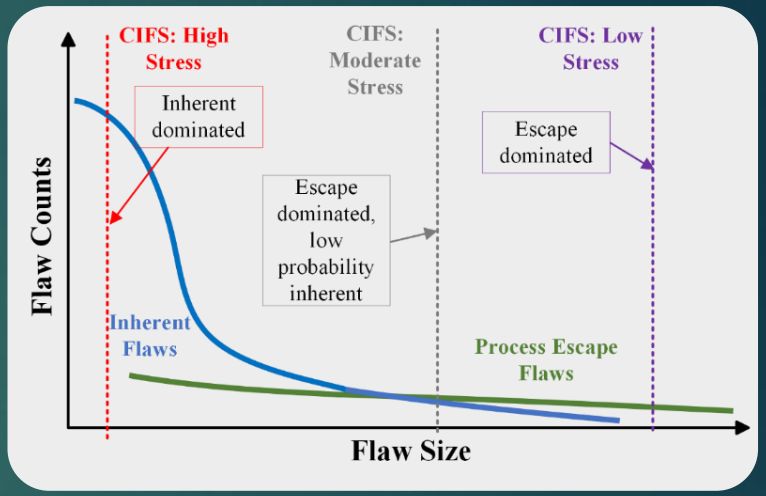
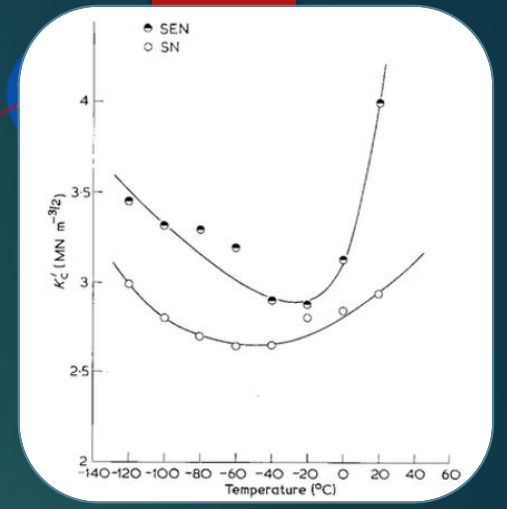
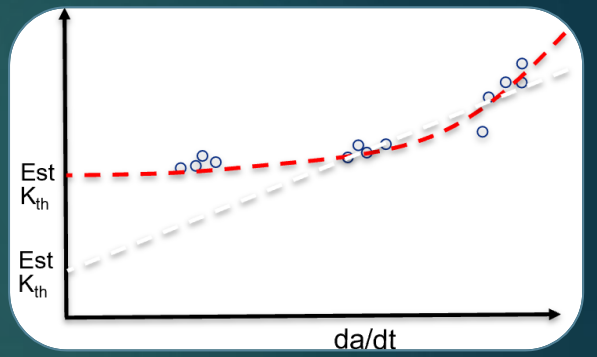
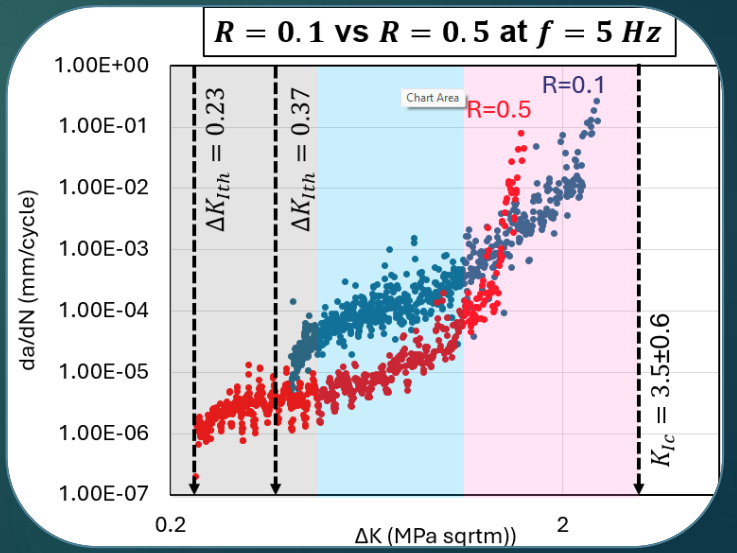


Polymers

- Material property sensitivities are different (more pronounced!) versus metals
  - Cycle-dependent (mean stress)
  - Time- and temperature-dependent (visco-elastic/visco-plastic)
    - Time dependence: load application rate and frequency, as well as duration
    - Temperature dependence: accelerates damage initiation and propagation
    - Material aging: time and radiation
  - Interactions between dependencies
- Modelling of individual sensitivities not well developed
  - Sensitivity interdependence definitely not well understood
  - Typical space usage: sustained load effects may dominate cyclic load
- Solutions
  - Structurally redundant design (may reduce fracture criticality)
  - Simulated service life testing with/without initial defects
  - Design below the crack growth threshold (expensive testing!)
- NASA Johnson Space Center has started focused testing to understand sensitivities and bound risk for spacecraft windows

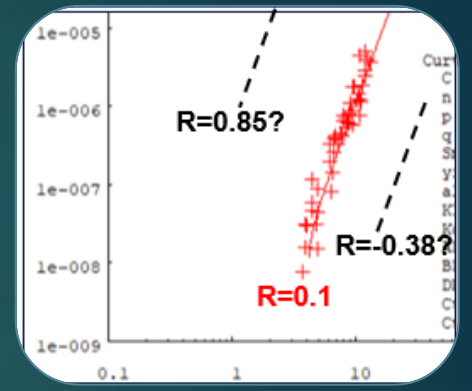


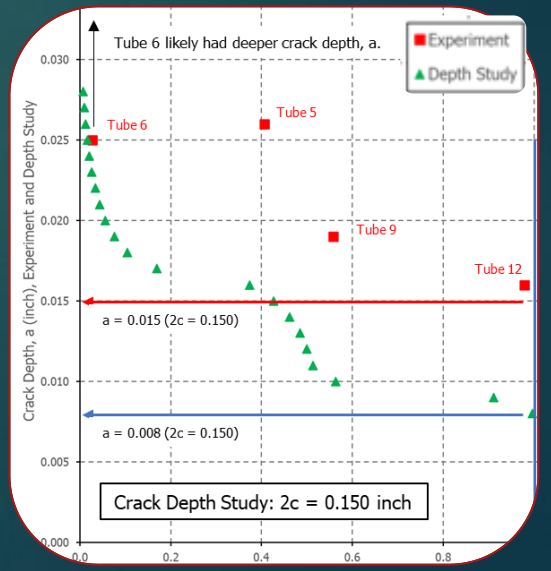




Case study: NDE and safe-life of Orbital Tube Welds

- Standard X-ray not sensitive enough for sufficient damage tolerance for small thin tubes
  - Detectability is a large surface flaw relative to depth: 0.150" x 0.7*t deep
    - ~20% of circumference for typical aerospace tube of 0.25"D x 0.028"t
  - Hardware provider: "our NDE is sensitive enough" but could not provide 90/95 POD evidence
- Analytical complications
  - No weld material properties (only parent): typical weld knockdown factors assumed
  - NASGRO data only for max/min stress ratio R=0.1 (actual usage R=-0.38 to 0.85): predictions based on extrapolation
- NASA conducted 2+ year test program of flight-like welds and loads
  - Successful notching, pre-cracking and fatigue crack growth testing in thin-walled tubing is a colossal challenge!
  - Tests substantially outperformed analysis, showing assumed material properties did not represent weld well
  - Allowed "leaning forward" to assume more analytical life capability but not enough for full service life
- Additional new analysis activities
  - Assumed slightly larger but more likely detectable flaw size (although also without 90/95 POD)
  - Provider-updated loads featured slightly reduced cycle count
- Final outcome
  - More locations attained sufficient damage tolerance life, while some locations will need mid-life attention
  - Some elevated residual risk due to use of flaw sizes without 90/95 POD (although more likely detectable)





Summary

- Damage tolerance lifing challenges are due to
  - Novel, cutting edge designs with complex geometries and new manufacturing techniques
  - Material property knowledge gaps (failure modes, characterization)
  - Failure to perform required damage mitigation activities (late implementation of fracture control protocol, or lack of flowing requirements to vendors, etc)
  - Programmatic priorities (funding and schedule preclude certain activities)
- Assessment methodology is necessarily always in "catch-up" mode with new technology
  - Understand the new materials. Manufacturing, designs through testing
  - Characterize the behavior for life predictions to the extent possible
- The new NASA paradigm: procuring services from commercial partners rather than owning hardware outright
  - Goal: fostering the space economy and to reach NASA objectives quicker and cheaper
  - NASA and its commercial partners have learned much from each other, and both are better off for it
  - More opportunities to grow the discipline
- It probably wasn't much different in the 60s when fracture mechanics came into its own
  - Smart people thinking outside the box to create solutions in keeping with safety requirements at acceptable levels of risk
  - The more things change, the more they stay the same!

Thank you for listening!

