Re-tooling the Agency's Engineering Predictive Practices for Durability and Damage Tolerance (D&DT)

Richard Russell
NASA Technical Fellow for Materials
Kennedy Space Center FL

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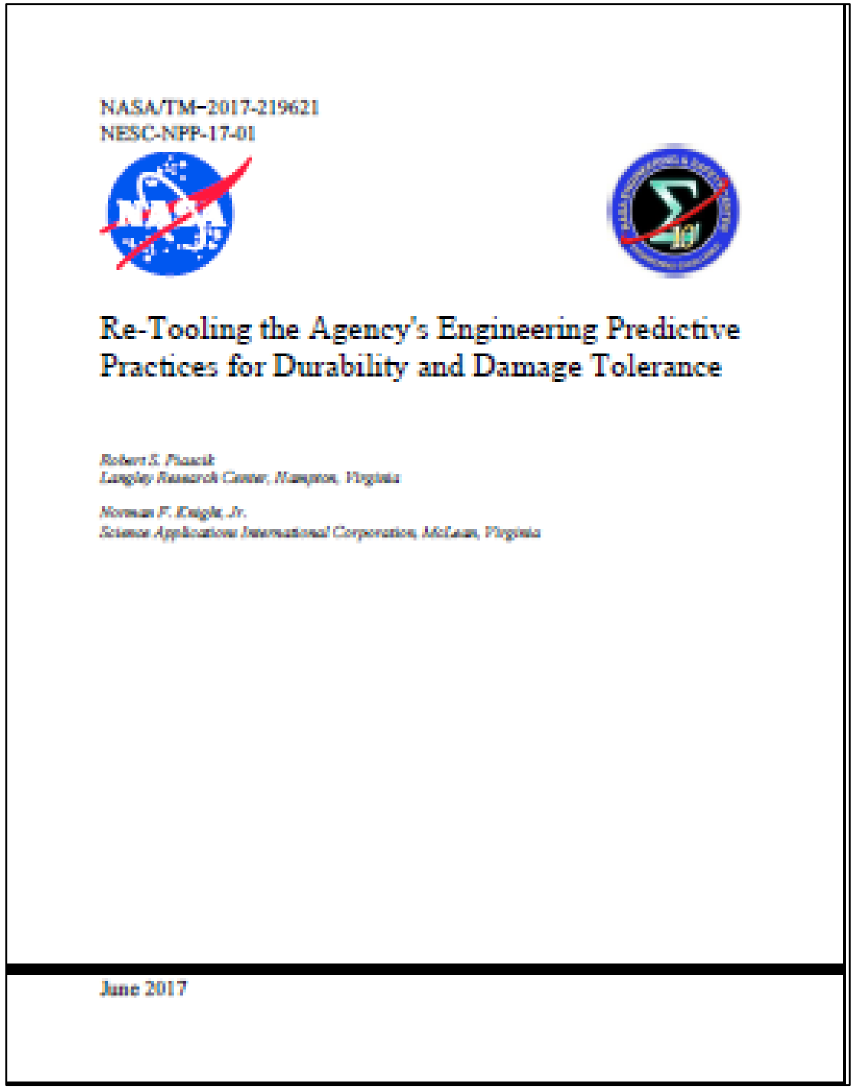
Acknowledgment and Motivation



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Re-Tooling the Agency's Engineering Predictive Practices for Durability and Damage Tolerance

Robert S. Piascik
Langley Research Center, Hampton, Virginia

Norman F. Knight, Jr.
Science Applications International Corporation, McLean, Virginia

June 2017

- As they wrapped up their NASA careers, Bob Piascik and Norm Knight saw the need for a *NESC Position Paper* that describes issues associated with the Agency's Durability and Damage Tolerance (D&DT) engineering standard practice.

- This report performed a critical review of the current standard engineering D&DT practices (Structures, Materials, and NDE) and the impact of future materials and processes on standard engineering D&DT practices

- The results of this review was published via a NASA Technical Memorandum in 2017

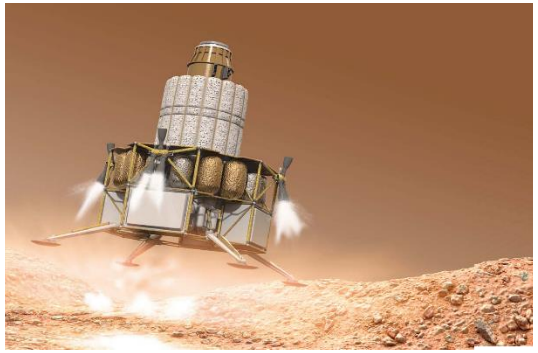

National Aeronautics and Space Administration
know your MARGINS
anchored to TEST DATA
at the BOUNDING CONDITIONS
UNDERSTAND FAILURES, WITHIN THIS CONTEXT

Importance of D&DT to Agency's Missions

- FACT: D&DT Understanding is critical to reliability
- FACT: Human exploration of deep space will require <u>extreme</u> reliability

Low Earth Paradigm

Deep Space Paradigm



250 miles vs 83,000,000+ miles
15-30 year life vs 50 to 100+ years
Replacement parts vs Limited replacement parts
Safe haven of earth vs no safe haven

Shortfalls in D&DT Technology

- D&DT technology gaps are occurring leading to the use of D&DT tools beyond their capability – <u>both analysis and test</u>.

- Shortfall in D&DT technology accelerating with more complex structural designs, new materials and higher performance requirements.

- Shortfall in D&DT technology exacerbated by demands of further weight reductions that will require <u>complex designs</u> and a <u>new understanding:</u>
  - Microstructural length scale influences
  - Multi-functionality capability
  - Complex local environments
  - Long-duration missions
  - Extreme reliability
  - Limited opportunities for inspection and repair

Examples of Technical Shortfalls

- Lack of recognition that some D&DT tools are inappropriate for some advanced designs/materials
- Lack of sufficient testing of new materials and their use to validate analysis methods/models
- Lack of understanding of fundamental assumptions, boundary conditions, and response metrics produced by the computational tools
- Lack of recognition of boundaries between conventional continuum mechanics and non-continuum responses
- Lack of capability to understand and evaluate local material behavior caused by increased reliance of global computational simulation results

Examples of Technical Shortfalls

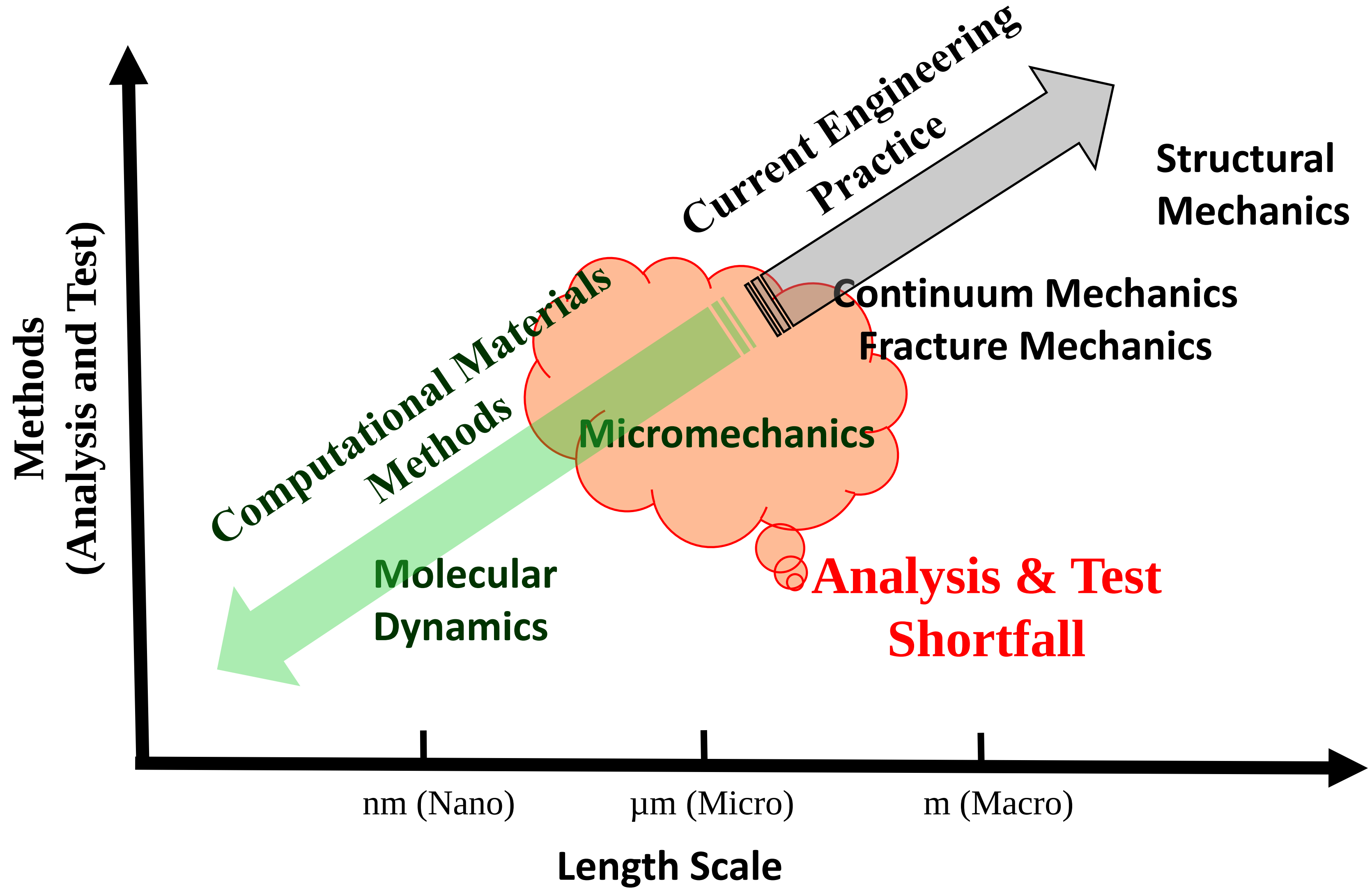
- Lack of understanding fracture mechanics similitude concepts and applicability of linear elastic fracture mechanics (LEFM)
- Lack of recognition of importance of local environments on D&DT assessment
- Lack of understanding the role of material length scales and increased dependencies on anisotropy and nonlinearities
- Lack of understanding and cross-communication of existing standard practice guidelines between disciplines

Primary Areas of Emphasis

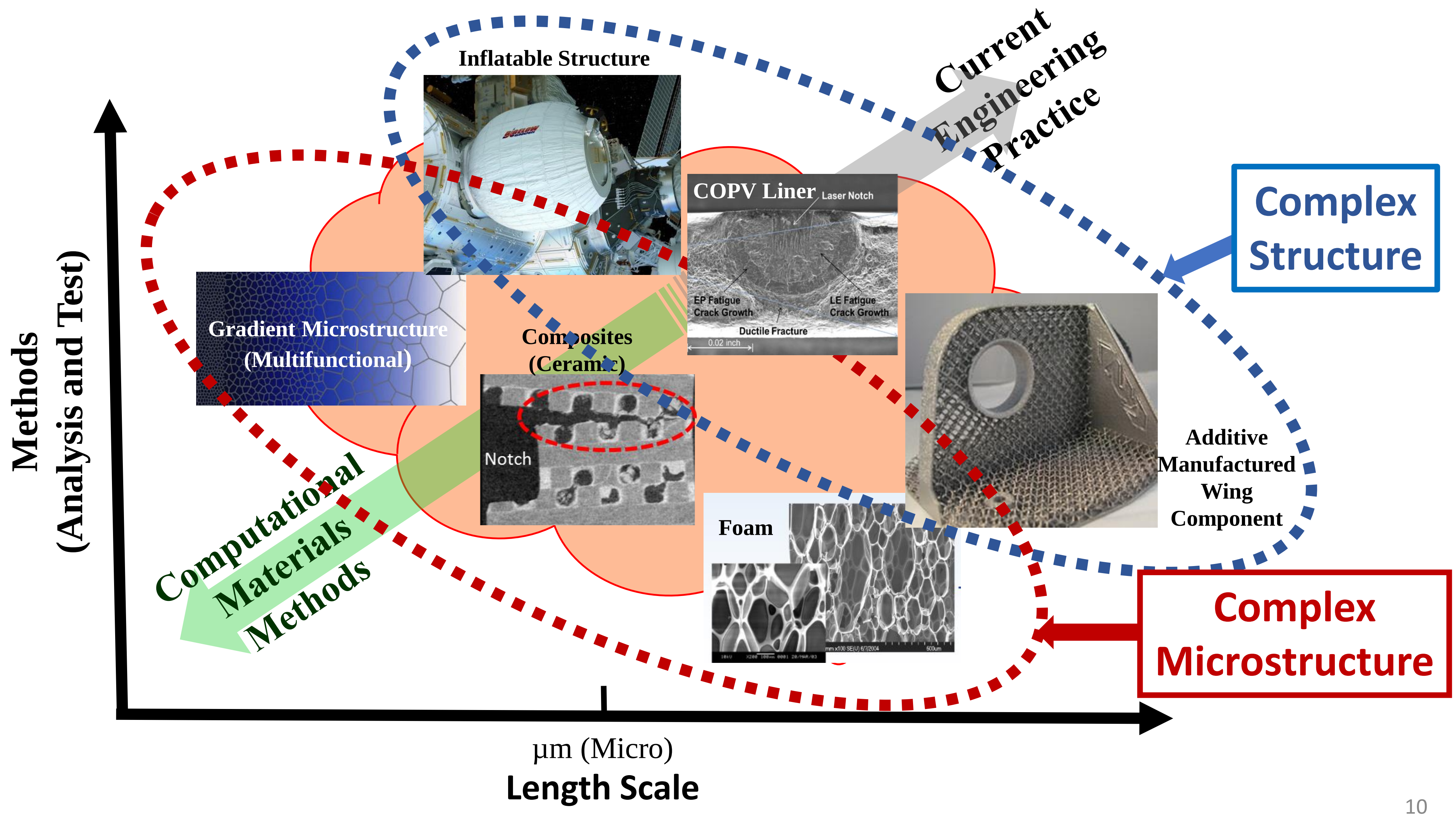
- Understanding and defining the technical limits of current engineering D&DT methods is paramount to ensure their appropriate use and reliability of their results.
  - Associated with technical rigor, understanding of the assumptions & limitations of the D&DT current methods and establishing effective communication interfaces among key disciplines.
- Developing advanced engineering computational tools for D&DT applicable across multiple material length scales when current engineering practices are realized to be inappropriate.
  - Associated with developing and maintaining an awareness of potential cross-disciplinary influences on a given design and developing computational materials models to address them.
- Developing material-length-scale-appropriate validation testing and inspection methods.
  - Associated with identifying and providing the appropriate material testing, property data, and inspection technology to validate new analytical methods and understand local material behavior.

D&DT

- Analysis and Test Methods -



D&DT Analysis and Test Shortfall (Micromechanics Regime)



Importance of *Local* Environment(s)

Failures resulting from D&DT issues are ALWAYS the result of a lack of understanding of LOCAL phenomenon!

- **D&DT assessment requires an understanding damage growth at the local level resulting from length-scale effects. Damage growth is solely governed by local environment.**
- **Careful consideration of environment related first-order effects are required for D&DT analysis and testing.**
  - **For example – conundrum of continuum versus non-continuum behavior**
    - Structural behavior? linear elastic, elastic/plastic, plasticity, complex configuration & length scale, etc.
    - Material behavior? Isotropy, ductile, brittle, bulk versus local properties, microstructural length scale, etc.

Agency’s Need for D&DT Re-Tooling

- Pockets of Computational Materials (CM) research and development are underway within the Agency
- Observations:
  - More CM R&D efforts outside than within the Agency
  - Most CM R&D efforts are working to mimic existing behavior
  - Insufficient, and perhaps inappropriate, material characterization testing for new materials and fabrication processes for relevant applications and environments to validate CM modeling
- Current D&DT engineering practice relies on commercially available existing tools and procedures and deemed sufficient rationale to reduce a factor of safety
- *Critical D&DT technology gap exists between computational materials R&D efforts and their integration or transition to D&DT engineering tools*

Agency's D&DT Engineering Tools Shortfall

Traditional D&DT Analysis Elements

- **Finite Element Stress Analysis**
  - Estimating local stresses – input for crack-growth analysis
  - Refined meshes, fast computers
- **Fracture Mechanics**
  - Estimating crack growth behavior (fatigue and fracture)
  - LEFM tools
- **Testing**
  - Materials Behavior - tensile, fracture, fatigue crack growth
  - Analysis Validation
  - NDE inspection

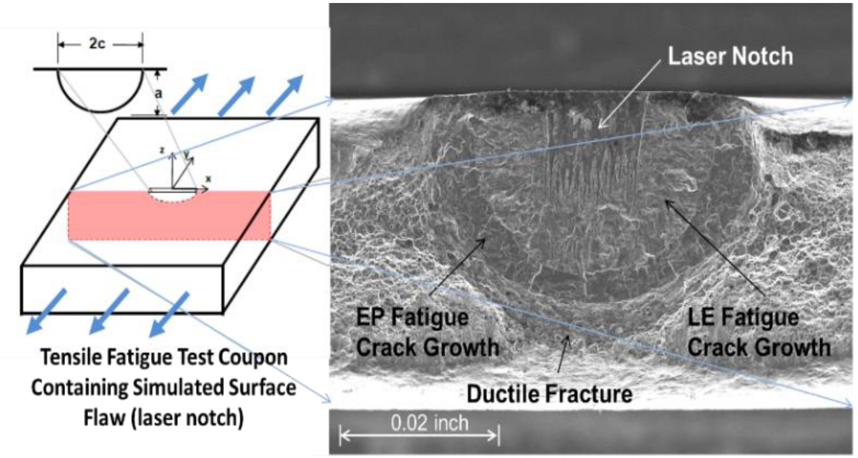
Technical Issues (Understanding Limits of Analysis Methods vs. Length Scale)

- **Finite Element Stress Analysis**
  - Inappropriate FEA results
    - Smaller mesh size is not always more accurate
    - Incorrect materials model: von Mises (ductile, isotropic), Continuum properties assumptions, etc.
- **Fracture Mechanics and Testing**
  - Incorrect use of LEFM Methods
    - LEFM Rules: Continuum, similitude, plasticity
    - Inappropriate test methods for small length scale

Therefore a New Technical Understanding is Required

Example: D&DT of Composite Overwrapped Pressure Vessel (COPV) Metallic Liners

- Human Exploration Programs and Science Programs are both currently using light* COPV's with 0.030- to 0.040-inch thick metallic liners.
- One of the current challenges in using *light* COPVs is adequate NDE.
  - The current NDE inspection methods occur prior to vessel autofrettage
  - Typically 0.050" long by 0.025" deep per NASA-STD-5009



SEM Micrographs showing a partial through-the-thickness ≈0.023 inch fatigue crack.

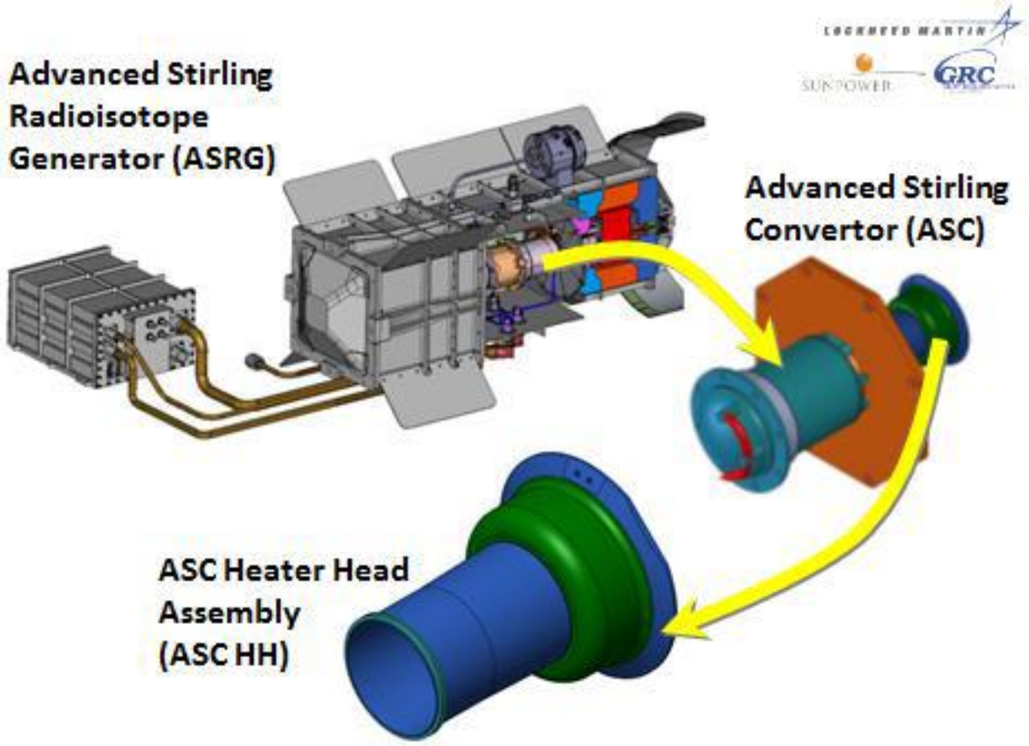
Note: EP - Elastic Plastic fatigue crack growth
LE – Linear Elastic fatigue crack growth

Example: D&DT of Composite Overwrapped Pressure Vessel (COPV) Metallic Liners

- Understanding the growth kinetics of small flaws is extremely complex and predicting the life of thin liner COPVs will require extensive work before it is achievable.
- Compounding the D&DT analysis is the fact that all liner flaw inspections occur prior to COPV autofrettage.
- Thin liners are susceptible to highly localized permanent deformations resulting from liner expansion (embossing)
- The current traditional engineering analysis paradigm may not apply adequate physics-based analysis tools and associated test methods that develop sufficient understanding for small material length scale designs.
- Currently, *light* COPV technology has surpassed the Agency's ability to predict performance and thus to understand and manage flight risks.

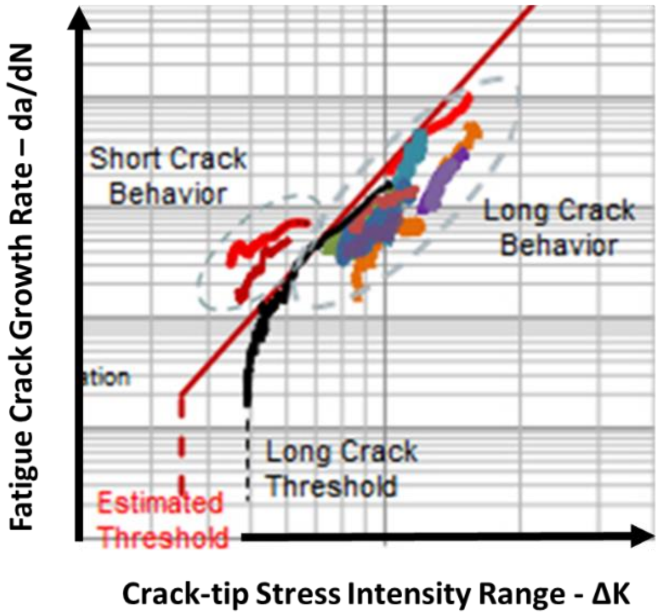
Example: Advanced Stirling Converter (ASC) Heater Head Fatigue/Crack Growth

- The NESC conducted a technical assessment to review the life-prediction results for a nominal thin-wall (0.005 inch) heater head component.
  - The design also required a cast MarM-247 component that contained large grains approaching the wall thickness dimension.
  - It was found that the Agency and its contractor were using LEFM-based methods to predict the fatigue life of the component.
  - The technical issue addressed was whether LEFM-based life-prediction methods can be used when a lack of similitude is indicated by accelerated small crack growth.



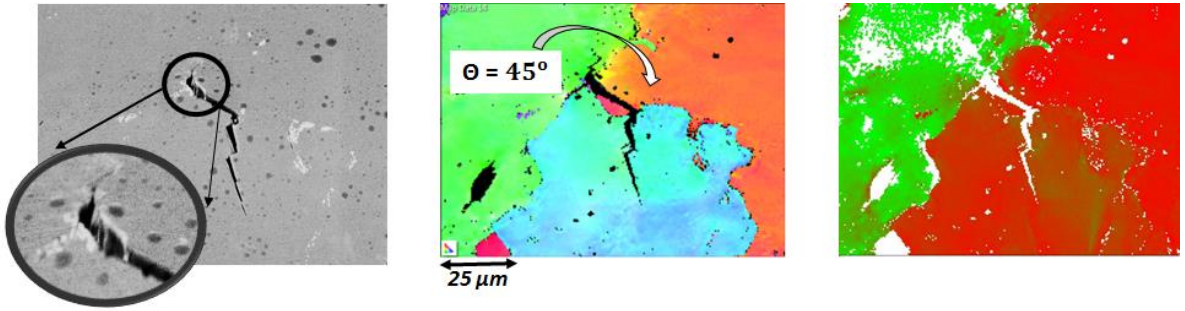
Example: Advanced Stirling Converter (ASC) Heater Head Fatigue/Crack Growth

- As seen in the figure the small (short) fatigue crack growth rates are accelerated compared to growth rates of long cracks.
- The NESC assessment concluded that LEFM is not capable of accurately and consistently predicting the fatigue crack growth (FCG) behavior of small cracks (i.e., small length scale cracks that approach the size of the microstructure).



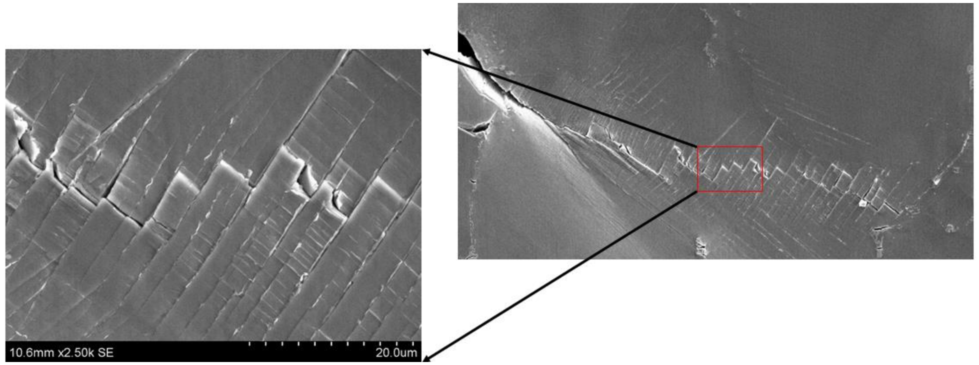
Example: Advanced Stirling Converter (ASC) Heater Head Fatigue/Crack Growth

- For large grain MarM-247 material, fracture-mechanics-based fatigue life-prediction methods must include either accurate FCG data established at the appropriate length scale or local stress and micromechanics models containing an understanding of the local damage processes



Micrograph showing small fatigue crack that initiated within carbide inclusion and crack growth in large grains where θ is the misorientation angle between two adjacent grains

Micrograph showing small fatigue crack morphology (complex slip-band cracking damage process) in large grain



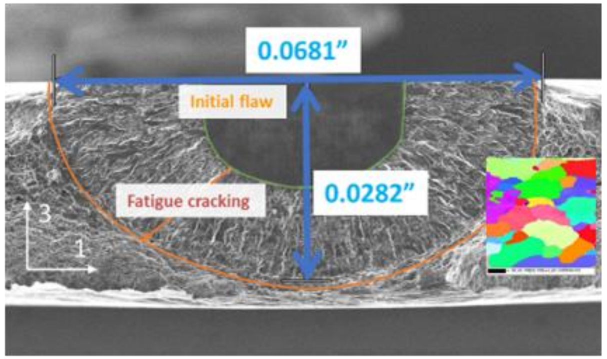
Short-Term D&DT: Needs and Recommendations

- **Needs**
  - Understanding the Limits of Engineering Methods
  - Need for Advanced Engineering Computational Tools
  - Validation Testing Needs
- **Recommendations**
  - Agency to provide sustained funding to re-tool D&DT standard engineering practice
  - Generate report cataloging the state-of-the-art, identify government & industry partners.
  - Establish an NESC multidisciplinary team (Materials, Structures, and NDE)
    - Address near term fixes
    - Plan to address complex longer term issues

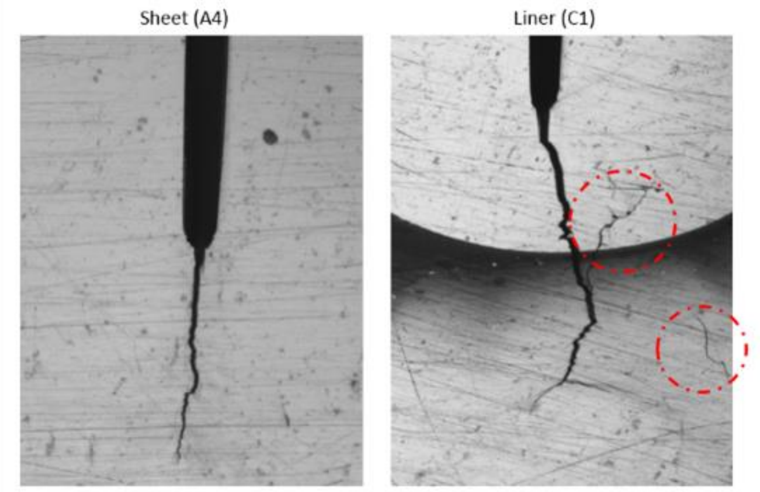
What’s next?

- NESC Assessment COPV Life Test
- Computational Materials
  - New NASA Intercenter Working Group
  - Budget request research and development
    - Thin walled COPVs
    - HIPed AM components
- New proposals to investigate “Effect of Length Scale and Microstructure for thin walled AM components”

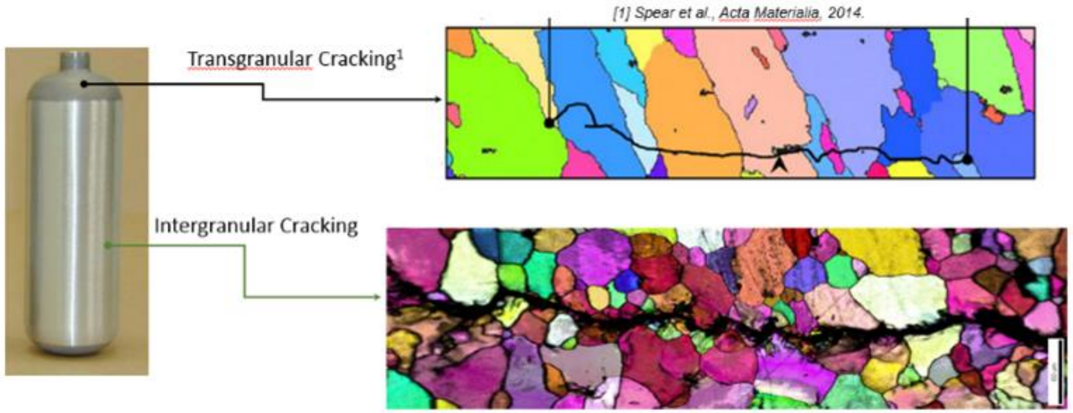
COPV Life Test

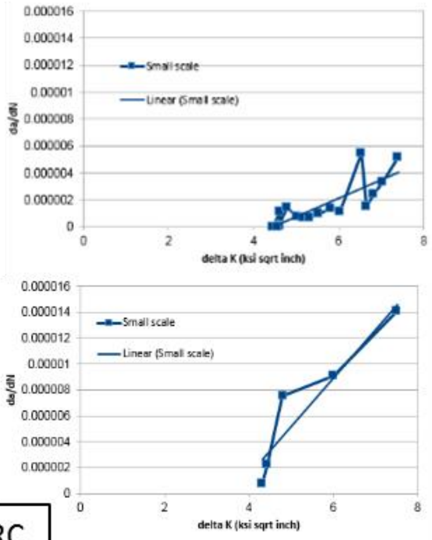


Flaws introduced using PFIB, able to characterize grains with EBSD.



Secondary cracking occurred in spun-formed material that does not form in sheet

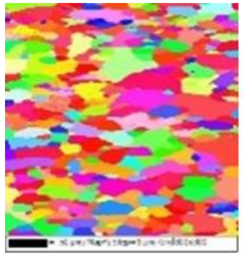




FCGR was higher in small grain material due to intergranular nature of crack growth. This grain size/FCGR relationship is not expected and could potentially be effect of spun-formed product.

All data from J. Hochhalter, et al, LaRC

Computational Materials
Development of Microstructurally Informed D&DT

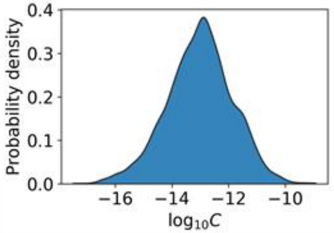


Characterize Microstructure using Quantitative Measurements

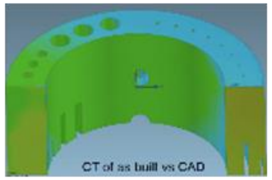
Localized FEA Models and Analyses Exploiting Fitted Measured Data

Microstructurally Small Crack Growth Model and Analysis to Understand Local Parameters

Fatigue Crack Growth Parameter Distributions

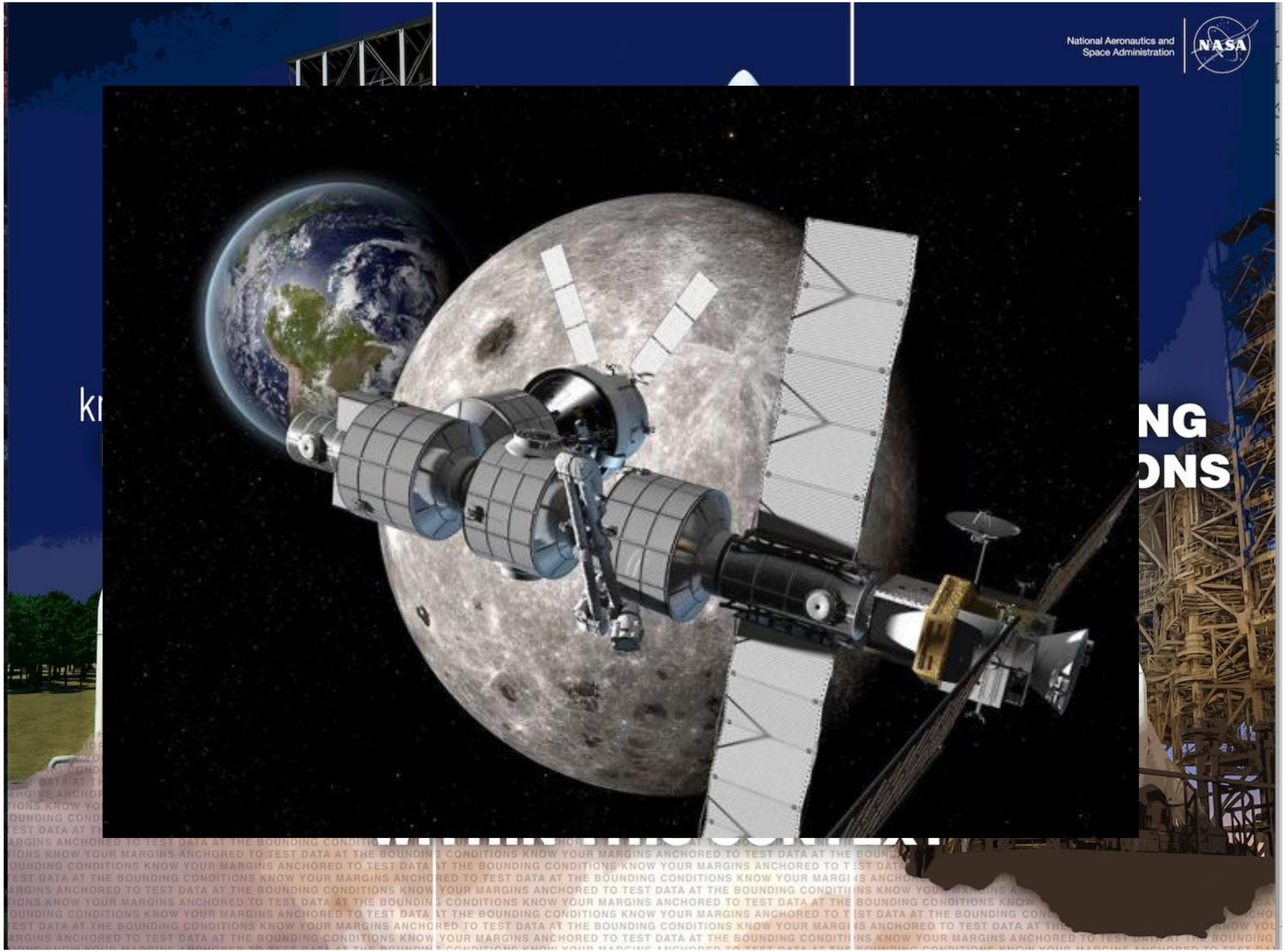


Global FEA Models and Analyses Subject to Service Environments



D&DT Analysis Tools (NASGRO, LEFM, EPFM, etc)

Today's D&DT Engineering Standard Practice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Questions??