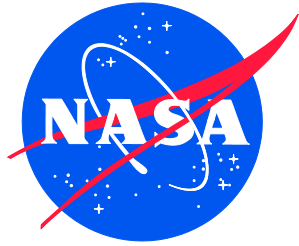# Re-Tooling the Agency's Engineering Predictive Practices for Durability and Damage Tolerance

Robert S. Piascik
Langley Research Center, Hampton, Virginia

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

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

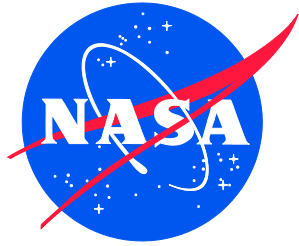- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

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

NASA Engineering and Safety Center
Position Paper

Re-Tooling the Agency's Engineering Predictive Practices for Durability and Damage Tolerance[1]

R. S. Piascik, PhD

NASA Technical Fellow for Materials (Retired)

and

N. F. Knight, Jr., ScD

Senior Principal Structural Engineer
Science Applications International Corporation

May 11, 2017

---

[1]The NASA Engineering and Safety Center (NESC) Review Board (NRB) approved this NESC Position Paper on May 11, 2017 (NESC-NPP-17-01).

Executive Summary

Over the past decade, the Agency has placed less emphasis on testing and has increasingly relied on computational methods to assess durability and damage tolerance (D&DT) behavior when evaluating design margins for fracture-critical components. With increased emphasis on computational D&DT methods as the standard practice, it is paramount that capabilities of these methods are understood, the methods are used within their technical limits, and validation by well-designed tests confirms understanding. The D&DT performance of a component is highly dependent on parameters in the neighborhood of the damage. This report discusses D&DT method vulnerabilities in terms of three important local parameters:

1. Local length scales (structural and material) within the micromechanics regime.
2. Local environments that have first-order influences on D&DT behavior. The report only discusses mechanical environments (stress and strain). Other local environments (i.e., thermal, chemical, radiation, etc.), while not discussed herein, must also be considered when deemed critical to D&DT performance.
3. Local material behavior (i.e., anisotropy, properties, damage mechanisms, etc.), that are often not properly or thoroughly considered during the test and analysis design process.

The lack of understanding of any of the local parameters listed above have led to incomplete and erroneous estimates of D&DT design capability. In this report, several vulnerable engineering practices related to estimating the D&DT of fracture-critical components are discussed. The report also discusses why D&DT method vulnerabilities will rapidly increase with new weight saving designs, advanced materials, and unique fabrication processes. The challenge of re-tooling D&DT methods is rooted in the need to rigorously address designs having complex material length scales and associated local environments that cannot be simulated by current D&DT analysis and test methods.

The objectives of the report are to expose potential vulnerabilities in the current D&DT engineering standard practice and to underscore the need for a multi-disciplinary re-tooling effort of the Agency's D&DT engineering predictive practices. The Structures, Materials, and Nondestructive Evaluation (NDE) disciplines must collectively work to re-tool the D&DT standard engineering practice. Three primary areas need to be emphasized. First, understanding and defining the technical limits of current engineering D&DT methods is paramount to ensuring their appropriate use and the reliability of their results. This area is associated with technical rigor: understanding of the assumptions and limitations of the current D&DT methods and establishing effective communication interfaces among key disciplines. Second, it is necessary to develop advanced engineering computational tools for D&DT applicable across multiple material length scales when current engineering practices are inappropriate. This area is associated with developing and maintaining an awareness of potential cross-disciplinary influences on a given design and developing computational materials (CM) models to address them. Third, it is also important to develop material length-scale-appropriate validation testing and inspection methods. This area is associated with identifying and providing the appropriate material testing methods, property data, and inspection technologies to validate new analytical methods and understand local material behavior. Recommendations suggest re-tooling the Agency's D&DT standard engineering practice.

1.0 Introduction

NASA's human space mission goals have focused on Low-Earth Orbit (LEO) for 60 years spanning the Mercury Program through International Space Station (ISS). This LEO paradigm for space system reliability is based on the following assumptions: 1) Limited lifetime (ISS designed for 15 year life and extended to nearly 30 years), 2) Replacement (components and parts are re-supplied as needed), 3) Unknown-unknowns (rapid fixes are transported from earth as needed), 4) Safe haven on Earth (one day return to Earth). Once we leave LEO and travel millions of miles, a new deep-space paradigm will need to be constructed based on different assumptions: 1) Extended lifetime (all assets are valuable in deep space), 2) Limited replacement (limited spare components and parts), 3) Unknown-unknowns (robust detection, analysis and repair), 4) Returning to Earth as a safe haven is a highly complex and dangerous endeavor. When comparing the LEO and deep space paradigm assumptions, it is obvious that ultra-reliable technologies will be required for deep space travel. These ultra-reliable technologies can be developed and deployed only through the understanding that comes from next generation D&DT methodologies.

The D&DT certification pendulum has swung too far as the Agency is relying too much on existing computational tools and standard engineering practices when evaluating design margins of some unique fracture-critical components. With increased emphasis on computational D&DT tools as standard engineering practice, it is paramount that these methods and tools be used within their technical limitations. Currently, complex local environments and local material behavior are often not properly or thoroughly considered, thereby leading to incomplete and erroneous estimates of the local D&DT response. The problem often stems from the fact that most analytical and computational procedures are currently formulated using conventional continuum mechanics theories that cannot treat failure mechanisms and modes arising from local material properties and local structural configuration, respectively. New designs, materials, and fabrication technologies push the limits of our modeling and understanding to demonstrate engineering predictive practices for D&DT. The reasons stem from the fact our models are not good enough, our material characterization is not sufficient, our understanding of damage and failure mechanisms is inadequate, and our testing is not extensive enough to understand the damaging effects of local environments. However, given these limitations and lack of true understanding of the material response, failures are still rare events. This is likely due to using conservative factor of safety, using well-characterized materials having statistically relevant material data, and perhaps ultra-conservatism related to loads and environments. We postulate that the Agency is entering a new era of deep-space travel that will require new weight-saving designs that must survive less tractable environments.

New designs come with unforeseen risks. Managing these unforeseen risks is becoming a real concern when the Agency's current technical approach is insufficient in some critical D&DT areas. The current engineering practice tries to minimize unforeseen risks with computational methods and tools that may be pushed to or even beyond their applicable limits and checked with a level of testing that may be insufficient. As a consequence, the limits of proven engineering practices are exceeded when applied to advanced designs that use new materials or fabrication processes. Sometimes these tools are applied without a full understanding of their technical limits or without appropriate testing and data to characterize the material response for local environments and loads. Understanding these limits results in properly using the current D&DT engineering predictive tools and recognizing the need for new D&DT engineering methods; that

is, re-tooling. The need for analysis and testing methods accounting for a range of material length scales is generally not recognized by the engineering community because of the explosive increase in computing resources and ease-of-use interfaces to commercial finite element analysis tools. Modern engineering tools can easily generate a refined finite element model (FEM) wherein the finite element size is reduced to very small scales but generally ignores microstructural features. These features can become important at such small scales and can influence the D&DT assessment.

The diagram shown in Figure 1.1 illustrates the important relationships of length scale with D&DT engineering practices and CM based methods. At the larger structural (macro) length scale (large arrow pointing upward to the right in the figure), structural mechanics, continuum mechanics, and linear elastic fracture mechanics (LEFM) accurately estimate global structural performance within their range of applicability. In this macro-regime, global and local finite element stress analysis models are developed and the results are used to assess D&DT capability at the macro-scale level with little regard to material length scales (see Appendix A). This macro-regime approach forms the basis for most of the Agency's current D&DT standard engineering practice and a large portion of the aerospace D&DT community. The methods are well understood, the material response is usually well characterized, the fabrication processes are well documented, and the environments are accurately defined for the macro-scale response.
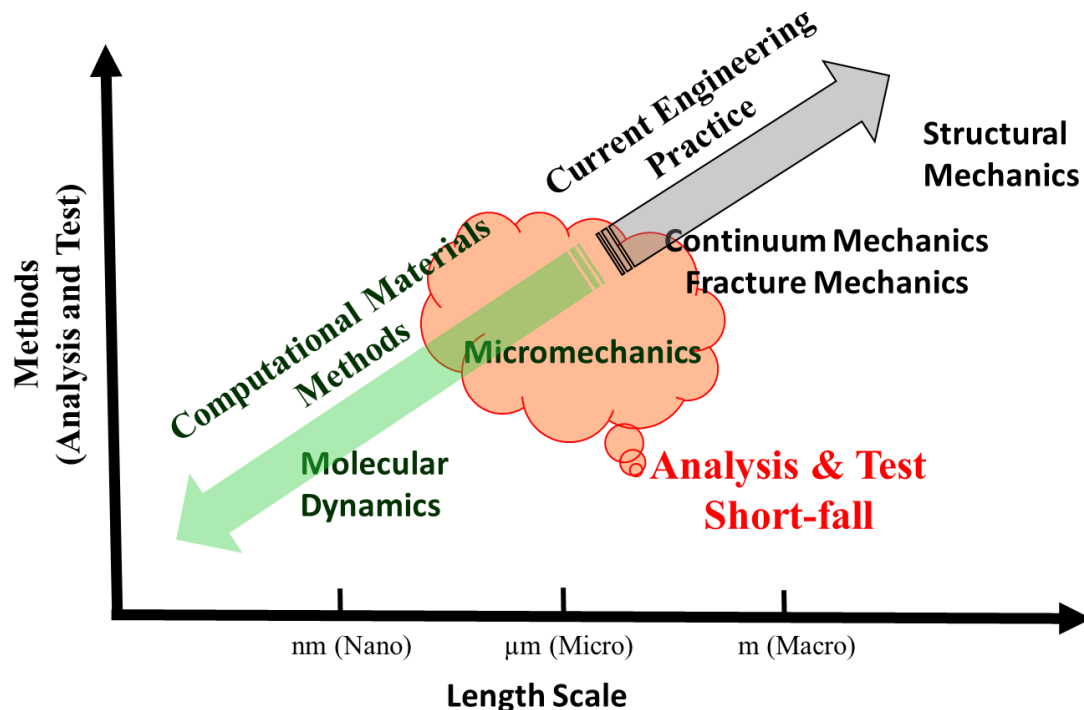
Figure 1.1. D&DT analysis and test methods as a function of length scale.

As critical structural length scales decrease and approach microstructure dimensions (micro length scale), the global continuum mechanics approach applicable at the macro-scale no longer applies. Multi-scale approaches are being introduced wherein the localization of micro-structural details is evaluated using representative unit volumes coupled with assumptions related to repeatability or periodicity. The results are then communicated to the macro-level through a

homogenization procedure. The influences of micro-structural effects are then represented as *effective* or *apparent* material properties using current standard engineering practices as indicated by the dark lines at the base of the upward pointing arrow in the Figure 1.1. Such multi-scale approaches tend to leverage the macro-scale D&DT approaches but potentially risk missing microstructural influences (e.g., structural length scale approaching the grain-boundary length scale). These approaches provide added insight into the global response at the expense of understanding damage initiation, propagation, and material failure at the microstructural level.

Micromechanics-based methods, local stress and strain state determination, local damage initiation and propagation understanding, and local microstructure-based material properties must be considered to assess D&DT performance for emerging new designs, new materials, and new fabrication processes. The arrow pointing downward to the left in Figure 1.1 is an indication that some Agency research activities in CM methods are underway but lack sufficient impetus and resources to overcome decades of neglect by the Agency. Fundamental research to provide engineering D&DT methods and tools for the emerging designs, materials, and fabrication processes has not been conducted at NASA. Conversely, other government agencies such as the Department of Energy (DOE) and the Department of Defense (DOD) have provided *substantial* and *sustained* funding for several decades to develop new mechanics models and computational approaches. These efforts are aimed at understanding the interplay between different material length scales and between structural and material length scales. However, there are still numerous shortcomings with the research methods and the transition from a research solution to an engineering capability represents a near empty set – a critical technology gap influencing near-term D&DT re-tooling. In recent years, it has become apparent that the Agency's current D&DT macro-based engineering practice has been inappropriately applied to estimate the performance of flight components that contain a critically small structural length scale and material (microstructural) length scale. This scale is depicted in the micromechanics regime highlighted by the center cloud shown in Figure 1.1 – the regime where the current D&DT analysis and test methods fall short.

Examples illustrated in Figure 1.2 are used to underscore the Agency's engineering practice shortfall.   New complex designs have incorporated small/thin structural elements (i.e., metallic Composite Overwrapped Pressure Vessel (COPV) liners), complex additive-manufactured components, and complex flexible structures (e.g., inflatable structures and habitats) whose D&DT performance cannot be reliably estimated by current engineering practices. In addition, new complex materials (i.e., gradient microstructure (multifunctional), advanced composites (polymer, metallic, ceramics), structural applications of non-structural materials (thermal protection systems, foams), etc.) containing complex microstructures will require new computational-materials-based methods to address even smaller/shorter length scales and properly estimate D&DT behavior. Because the Agency is currently focusing on new complex weight-saving structural concepts that require micromechanics length scale methods, the Agency must critically assess its D&DT analysis and test capabilities to insure that the proper D&DT understanding is developed prior to flight.
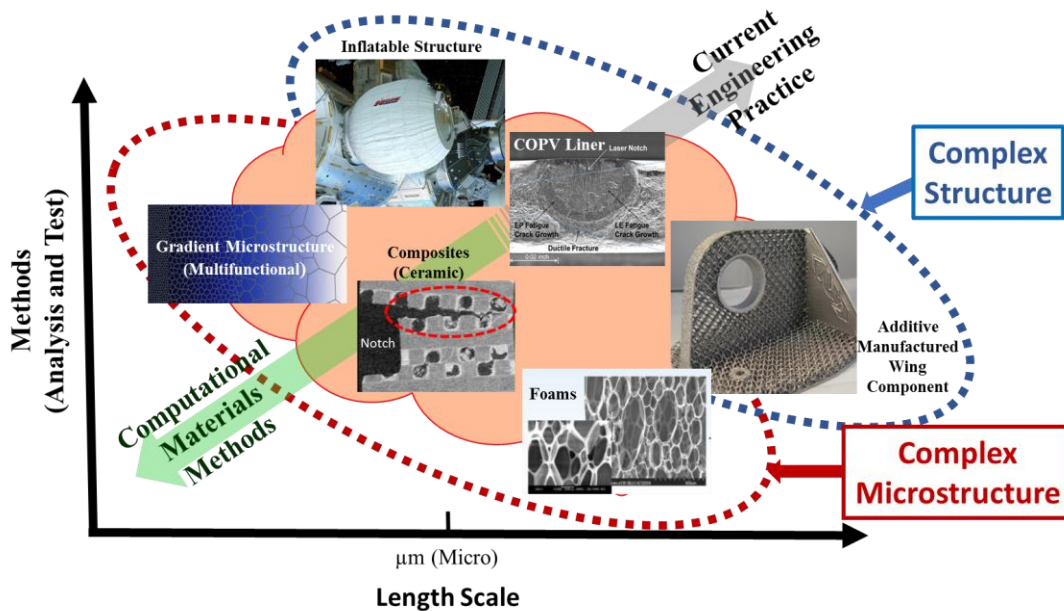
Figure 1.2. Examples of D&DT methods short-fall within the micromechanics length scale regime.

1.1   Objectives

The first objective of this report is to identify potentially vulnerable engineering practices related to estimating and predicting the response of fracture-critical components that challenge the current standard D&DT methods. These challenges result from the need to address multiple material length scales in assessing D&DT requirements for future aerospace systems. Vulnerabilities are associated with using the current D&DT analysis and testing methods that are primarily focused on macro-scale responses to provide accurate and valid estimates of material behavior across different material length scales and to provide a greater understanding of the influence of local environment(s). This report discusses some of the causes for the D&DT analysis and testing technology gap.

The second objective of this report is to highlight the need for heightened awareness by the engineering community of the limitations of the current D&DT tools as the Agency pursues new materials and processes required for complex aerospace designs.[2] While pockets of CM research and development are underway within the Agency, current D&DT engineering practice relies on commercially available existing tools and procedures with those results deemed sufficient rationale to reduce a factor of safety. A critical technology gap exists between these CM research and development efforts and their integration or transition to D&DT engineering tools. It is hoped that this report will drive home the importance of and reinvigorate the establishment of a long-term, sustained multi-disciplinary effort to bolster the Agency's D&DT research and

---

[2] The NASA Engineering and Research communities have been aware of some of these limitations. A Foundational Engineering Science initiative within the Agency was attempted a number of years ago but has lost focus.

tools development required by the 21st century aerospace community – a re-tooling of the Agency's D&DT engineering predictive practices.

1.2   Path Forward

The Structures, Materials, and NDE disciplines must collectively work to re-tool the D&DT standard engineering practice. Understanding our current tools and their limits is a critical first step in the re-tooling process – our existing tools are valid for many cases. *Communication* across and between disciplines needs to be strengthened and enhanced, in particular, a common vocabulary and language must evolve across workforce and management levels. Examples of vocabulary and language disconnects include the perception that a finite element meshing equates to *modeling* or that finite element meshing based on solid geometry definition defines *high-fidelity*. *Collaboration* between disciples is needed as D&DT is such a broad sub-discipline that no single discipline has the answer. *New D&DT tools* (tests and methods) applicable to new designs, materials, and processing need to be developed and transitioned from D&DT research topics to new engineering D&DT tools. Finally, *education* is needed to enlighten Agency Programs of the importance of using the appropriate D&DT methodologies and that the D&DT community understands the capabilities and limitations of the D&DT tools.

Furthermore, as new designs, materials, and fabrication processes emerge, the importance of material length scales in the micro- and nano-range is anticipated to increase. Understanding the influence of these effects on the D&DT of future flight systems will necessitate further research in CM for discrete continuum mechanics, molecular dynamics and atomistic mechanics. It is anticipated that such long-term efforts will be enabled by parallel developments in computing systems – both hardware and software. These future advances must be developed with the perspective of providing future generations of D&DT methods and tools – re-tooling.

Three primary areas are recommended as needing attention. First, understanding and defining the technical limits of current engineering D&DT methods is paramount to ensuring their appropriate use and the reliability of their results. This area is associated with technical rigor: understanding the assumptions and limitations of the current D&DT methods and establishing effective communication interfaces among key disciplines. Second, it is necessary to develop advanced engineering computational tools for D&DT applicable across multiple material length scales when current engineering practices are inappropriate. This area is associated with developing and maintaining an awareness of potential cross-disciplinary influences on a given design and developing CM models to address them. Third, it is also important to develop material length-scale-appropriate validation testing and inspection methods. This area is associated with identifying and providing the appropriate material testing methods, property data, and inspection technologies to validate new analytical methods and understand local material behavior. These recommendations suggest re-tooling the Agency's D&DT standard engineering practice.

1.3   Acknowledgements

and Dr. Vinay Goyal (The Aerospace Corporation). The authors would also like to thank all the members of the Materials TDT and the Structures TDT. Their review comments and insights were greatly appreciated.

2.0   Background

Over the past decade, the Agency has placed less emphasis on testing and has increasingly relied on analytical and computational procedures to understand and assess durability[3] and damage tolerance[4] (D&DT) behavior when evaluating design margins for fracture-critical components. While this trend has the perceived advantage of reducing schedules and costs, the D&DT community needs to recognize and address potential material length-scale (see Appendix A) issues as they relate to D&DT methods to not compromise safety unknowingly.

Currently, complex local environments (highly localized stress and strain responses) and material behavior are often not considered, thereby leading to incomplete and erroneous estimates of the local D&DT response. The problem often stems from the fact that most analytical and computational procedures are currently formulated using conventional continuum mechanics theories[5] that cannot treat failure mechanisms arising from local material microstructural effects (see Ref. 1). Consequently, results extracted from such continuum-based global analysis models can lead to erroneous D&DT results when applied to designs and materials exhibiting length-scale dependencies. One example of length-scale dependencies arises either from small defect sizes or small uncracked ligaments both of which can violate LEFM assumptions[6]. Another example arises from complex material microstructures that cause anisotropic material behavior leading to stress concentrations along grain boundaries, and interactions between failure mechanisms (see Ref. 1).

Often the current engineering practice advocates developing detailed, large-scale finite element analysis (FEA) models of a structural component under the premise that material length scales are related to the size of a finite element within the mesh. Such global FEA models impose boundary conditions, loads, and environments defined at the macro-level to estimate strains and then determine stresses using a continuum-based material model tied to standard material properties derived from coupon tests. These trends are described in Section 3.0. Some FEA models may include a defect or crack wherein local deformation, stress, and strain estimates are extracted. These estimates are used as input to fracture mechanics and fatigue tools to assess D&DT capability. Results from such FEA models and LEFM estimates are frequently perceived to be accurate and credible even though they could be beyond the capability of the FEA models. The results were likely computed using material models developed and validated for macro-scale continuum problems where scale independence was demonstrated to apply. Examples from

---

[3] The ability of the structure to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a prescribed period of time (from MPCV 70135, Orion Multi-Purpose Crew Vehicle (MPCV) Program: Structural Design and Verification Requirements (SDVR), Rev. A, June 9, 2015).

[4] The attribute of a structure that permits it to retain its required residual strength for a period of unrepaired usage after the structure has sustained specific levels of fatigue, corrosion, accidental, and/or discrete source damage (from MPCV-70135).

[5] Conventional (scale independent) continuum mechanics theories assume a length scale generally related to the structure being analyzed and exhibit an independence from material length scales. Scale-dependent continuum mechanics models take into account the dependence of a material's response on the physical phenomena occurring at the appropriate material length scales.

[6] The underlying fundamental assumptions of LEFM are (i) the material away from the crack tip undergoes elastic deformations; (ii) the plastic region ahead of the crack tip is small in relation to the length of the crack; (iii) deformations outside the small plastic regions are presumed to remain elastic; and (iv) the material is presumed to have a grain structure such that the integrated effects of the grains in these regions act as a continuum.

previous NASA Engineering and Safety Center (NESC) assessments are cited in Section 4.3 of this report. These examples show when length-scale-based tenets have been unrecognized or ignored and hence violated by a global analysis approach advocated by the current D&DT standard engineering practice.

Such engineering practices related to estimating/predicting the safe life of fracture critical components[7] whose design and fabrication challenge standard D&DT methods raise potential vulnerabilities. Vulnerabilities are associated with current D&DT analysis and testing methods focused on macro-scale responses requiring accurate estimates of material behavior across different material length scales and greater understanding of local environment(s). These vulnerabilities are becoming more evident with the development and integration of advanced material systems and material architectures (e.g., advanced alloys, multi-directional composites, multifunctional materials), with the application of advanced fabrication and manufacturing technology (e.g., advanced fiber placement and additive manufacturing), and with the increased demand for reduced weight and increased performance (to support interplanetary missions and human outposts).

3.0   Current Practice

Current engineering standard practice for D&DT predictions is unable to provide, through analysis and testing, the understanding required to ensure safe and reliable flight of new complex vehicle designs based on advanced materials and fabrication processes. Once this inadequacy is recognized, the D&DT predictions fail to capture the required technical understanding of the small length-scale failure mechanism due to test and inspection limitations. This problem is exacerbated either by the enormity of the computational task associated with microstructural modeling and simulation or by the complexity of defining and obtaining the relevant material properties of advanced materials and fabrication processes. In fact, quantifying material properties in complex materials requires developing new testing and inspection methods and advanced CM models. These models must incorporate the fundamental microstructural interface properties across multiple material scales that often control the operative failure mechanisms. Thus, it is concluded that a new class of damage-science-based predictive tools is required to accurately represent the damage initiation and failure mechanisms necessary for accurate D&DT predictions and to ensure mission success and safety. In the interim, the role of testing for characterization and certification needs to be elevated. Moreover, maturing such advanced D&DT methods from a research and development framework to standard engineering practice (i.e., a new normal) is crucial for future Agency spaceflight missions that exploit the emerging materials and fabrication technologies required to meet ever higher performance requirements safely.

The Agency's Safety and Mission Assurance (S&MA) organization has succinctly captured the proper tenets to ensure understanding of risk. These tenets are based on technical rigor rooted in physics-based approaches to both testing and analysis and they outline the fundamentals of good engineering practice. The following seven tenets from S&MA have been slightly modified to suit the notions developed herein and are listed here with multiple material length scales included as one key factor.

---

[7] Fracture critical components are parts whose individual failure, caused by the presence of a crack, is a catastrophic hazard and that requires safe-life analysis or other fracture control assessment to be shown acceptable for flight. Ref: NASA-STD-5019A.

1. <u>Solid technical understanding</u> – Physics-based or root-cause understanding of technical issues associated with the design, based on sound engineering anchored with testing under relevant loading and environmental conditions. This tenet requires recognizing the limitations of standard practice tools and of the potential impact that designs with multiple material length scales may have on the tools' applicability.

2. <u>Condition relative to experience base</u> – Experience is based on tests and validated analytical tools and is influenced by the background and seasoning of test engineers and analysts. This tenet requires an awareness and understanding of advances in material science and fabrication technology by inclusion of next generation D&DT methods and tools.

3. <u>Bounding case(s) established</u> – Using physics-based understanding from validated analytical tools and anchored with tests, determine bounding case(s) for the mission based on a thorough understanding of environments, mission requirements, and the use of non-deterministic[8] approaches. This tenet requires uncertainty quantification to understand risk and should include an assessment of appropriate material length scales.

4. <u>Self-limiting aspect</u> – Understand the physical reasons why a bounding case is truly bounding or show the part is fail-safe – that is, damage tolerant[9]. This tenet requires the material response to be consistent across different material length scales and accounts for local environments.

5. <u>Margins understood</u> – Maintain adequate margins of safety, ideally, not substantially reduced from the baseline. Margins are essential to protect the system or vehicle from potential threats that may not be well understood. This tenet requires an understanding of the dependence (or independence) of the margin of safety assessments across material length scales with potentially different failure mechanics emanating from different scales.

6. <u>Risk Assessment based on test data and analysis</u> –Minimize engineering judgment. As the complexity of the new designs increases, and as new materials and manufacturing processes are incorporated, engineering judgment may be inadequate or even detrimental. This tenet requires a re-tooling of standard engineering practices to accommodate emerging material systems and fabrication technologies and address multiple material length scales.

7. <u>Consider interactions between critical elements/conditions</u> –Understand and mitigate design sensitivities. The design should be as robust as possible without known potential susceptibilities that could compromise safety. This tenet requires thorough assessment of the known unknowns and recognition that unknown unknowns remain for high-performance designs using advanced materials, concepts, and technologies.

Because these tenets are anchored by rigorous engineering practices, the engineering community must constantly ensure their computational tools and their inputs are truly appropriate so that system performance and risk can be correctly estimated with confidence and managed appropriately. While not a new problem, it has been exacerbated by the integration of new materials, complex designs, and new fabrication processes. Current engineering computational tools and tests methods are not capable of quantifying design margin and associated risk for

---

[8] These non-deterministic approaches would deviate from current deterministic continuum mechanics methods to accommodate effects such as different material length scales when predicting material and structural responses.

[9] A fail-safe assessment demonstrates structural redundancy in the event of loss of one load path and includes evaluating structural margins for redistributed static and dynamic loadings.

these new cases when multiple material length scales are important. Sometimes, the need to model multiple length scales is not recognized. This limitation and challenge is particularly true when test data are limited, when environments cannot be simulated in ground tests, or when operational environments are unknown or uncertain. Often, statistically relevant material allowables cannot be generated due to cost, schedule, or the lack of available material to test. In addition, newer materials may necessitate the development of alternate or additional material tests or characterization methods to determine actual material allowables applicable for that material system or manufacturing approach (e.g., additive manufacturing, advanced fiber placement). These result in different material length scales to be evaluated for D&DT.

Current engineering practices often use large-scale global finite element analyses of a test coupon, structural element, or component (i.e., macro-scale modeling) to compute local response. The premise is that local stress states may be obtained using local strain estimates and continuum-based material models and global response metrics. Advances in computation power have enabled global finite element analyses to be performed with finer and finer meshes with the assumption that the more refined the mesh, the more accurate the local stress prediction will be. However, bigger is not always better and does not guarantee a valid solution. Finite element mesh refinement is needed to demonstrate convergence of the discrete analysis model, its underlying assumptions, and response parameters as part of the verification process. Some engineers may even assume that accurate microstructural response can be predicted as the mesh size (characteristic length of a finite element) approaches the microstructural scale of the material. These assumptions are not correct and lack the required technical understanding. The computations become increasingly compromised without a basic understanding of length-scale-related material properties and strain-localization/microstructure that govern damage processes combined with the false assumption that a more refined FEM leads to more understanding. The material length scales (see Appendix A) referred to herein are associated with critical local properties and mechanisms that must be incorporated into the CM model within the analysis tools, and are not associated with the characteristic length of a finite element (mesh size) within the analysis model.

The need for more efficient spacecraft designs for long-duration robotic and human space flight is challenging the Agency's D&DT standard engineering practices. Central to safe long-duration space flight is understanding D&DT and providing a credible D&DT predictive capability. Compounding the never-ending challenges of space flight, such as the one-of-kind vehicle designs that must survive unique extreme environments, is the current challenge of long-duration human exploration. The engineering community must be reminded of the limits of current engineering analysis tools, testing methods, and associated standard practices and must be vigilant in their use. Specifically, the computational mechanics community recognized the significance of the previously mentioned improper or inappropriate use of the current standard engineering methods, and took action to understand and resolve these issues. The Agency should proceed with identifying and developing advanced computational engineering tools validated by appropriate tests and NDE inspection methods, thereby re-tooling the Agency's D&DT capabilities and enhancing engineering predictive practices for future aerospace systems. This will create a new normal of standard engineering practice.

4.0 Motivation and Challenges

The Agency's Human Space Flight Programs are moving forward with qualifying commercial partners' LEO vehicles, new launch/space vehicle designs, and habitat concepts for deep-space exploration. The Agency's Robotic Program is also concentrating on more efficient, but even more complex designs subject to extreme environments and interplanetary missions. As these complex Agency missions mature, it is imperative that engineering methods and simulation results that mimic system response to environments and local D&DT phenomena, are scrutinized to ensure that thorough technical understanding is established prior to the design, development and certification phases. Over the past decade, new designs have become understandably more complex because of the need for increased efficiency and performance (e.g., reduced weight, enhanced load-carrying capability, improved thermal performance, etc.). Each new design typically contains new technical complexities and associated risks that engineering must not only quantify, but more importantly recognize and understand. Programs then routinely accept risk with the expectation that engineering has addressed all knowledge gaps in understanding the D&DT aspects of the new designs and fabrication processes, in characterizing material behavior and failure mechanisms, and in identifying global and local environments and operational requirements. They expect that the appropriate and applicable D&DT computational tools and test methods were used to properly assess design safety margins. However, on occasions the current engineering process has failed to recognize one or more knowledge gaps, or has failed to be astute enough to ask questions that may challenge the status quo. Often times, engineering judgment derived from past experiences does not contain sufficient technical understanding or rigor when applied to these new designs or new configurations or new materials with the system having high-performance requirements for mission success.

4.1 Traditional Analysis Paradigm versus Required Technical Understanding

New and more complex designs are subject to high-performance operational requirements and are potentially operated in extreme environments with minimal or no possibility for inspection or repair once deployed. These new designs use unique light-weight configurations, exploit advanced materials and innovative fabrication processes, and challenge our ability to provide a credible and accurate design safety margin assessment. This issue has surfaced at an increasing rate suggesting that current D&DT engineering computational methods used by the Agency, and its contractors, are becoming outmoded for some advanced fracture-critical designs. Lack of recognition that some of our conventional computational tools are inappropriate can have serious consequences on mission success as predictive analyses are being increasingly relied upon with less emphasis on costly testing. Using outmoded and inappropriate computational tools for new complex designs and materials directly impacts the Agency's ability to predict safe-life performance accurately. New complex design configurations that have been enabled by advanced materials and innovative processes (e.g., additive manufacturing, component designs with small length scale, micro-electronics, etc.) have created a gap in understanding local material response and its impact on material modeling and testing. Current computational methods are not capable of developing the fundamental understanding at the critically small length scales needed to predict appropriate material response metrics (Ref. 1-8).

The lack of understanding is exacerbated by the persistent using traditional engineering analysis paradigms that *may not apply* where small length scale understanding is required. For example:

- Inappropriately accepting finite element results based on mesh density, using three-dimensional solid geometries developed with computer aided design tools, and using a particular FEA tool. The perception that when the smallest element size in a finite element mesh approaches the material grain size then microstructural effects are automatically included in the model is false.
- Lack of understanding of fundamental assumptions, boundary conditions, and response metrics produced by the computational models.
- Inability to define and recognize the boundaries of applicability for conventional continuum mechanics assumptions.
- Inappropriate use of LEFM due the violation of its fundamental assumptions.
- Lack of understanding of fracture mechanics similitude concepts[10] leading to the potentially inappropriate use of engineering tools such as NASGRO® (Ref. 9).
- Inappropriate use of finite element stress results (such as a calculated point stress or an augmented stress metric such as the von Mises stress[11]) leading to the inability to understand and evaluate local material behavior and ignores local triaxiality and directional dependence.
- Lack of recognition of the importance of local environments (e.g., local loads, load redistribution, and interfacial strain, etc.).
- Lack of understanding of material length scales and their influence on material behavior at multiple length scales such as increased dependence on local material anisotropy and nonlinearities at small length scales superimposed on directional dependencies at larger length scales.
- Lack of understanding across disciplines of existing standard practice guidelines such as American Society for Testing and Materials (ASTM) E647, Standard Test Method for Measurement of Fatigue Crack Growth Rates[12].

---

[10] The Similitude concept implies that, for two different sized cracks subjected to equal stress intensity values (under small-scale yielding) in a given material-microstructure-environment system, crack tip plastic zones will be equal in size and the stress and strain distributions along the borders of these zones (ahead of the crack) will be identical. Accordingly, equal amounts of crack extension (Δa) will be expected. See Ritchie and Suresh (Ref. 3).

[11] To apply the uniaxial stress-strain model, an effective stress is defined typically using the von Mises stress, σ_{vM}, which can be written in terms of the three principal stresses as:

$$\sigma_{eff} \equiv \sigma_{vM} = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}$$

The von Mises stress criterion compares this effective stress to the yield stress from a uniaxial tension test data and assumes a linear elastic, isotropic, homogeneous ductile material and ignores any directional dependencies.

[12] ASTM E647 (Ref. 10), Paragraph 5.1.5 - The growth rate of small fatigue cracks can differ noticeably from that of long cracks at given ΔK values. Use of long crack data to analyze small crack growth often results in non-conservative life estimates. The small crack effect may be accentuated by environmental factors. Cracks are defined as being small when 1) their length is small compared to relevant microstructural dimension (a continuum mechanics limitation), 2) their length is small compared to the scale of local plasticity (a linear elastic fracture mechanics limitation), and 3) they are merely physically small (<1 mm). Near-threshold data established according to this method should be considered as representing the materials' steady-state fatigue crack growth rate response emanating from a long crack, one that is of sufficient length such that transition from the initiation to propagation stage of fatigue is complete. Steady-state near threshold data, when applied to service loading histories, may result in non-conservative lifetime estimates, particularly for small cracks.

These concerns and issues limit the Agency's ability to develop technical understanding and consequently burden engineering's ability to ensure that risks associated with a new design are identified, understood, and properly quantified and that their consequences are communicated and managed.

4.2   Examples: Inability to Assess D&DT

Based on a review of past Materials and Structures Discipline-related NESC assessments conducted over the past 10 years, there is a troublesome trend showing that important Engineering methods have been misapplied and/or their results misinterpreted or oversold. Often analysis results obtained from refined FEMs are presented with a tacit assumption that the results from such an analysis must be accurate since they were executed with one of our traditional tools using a very refined FEM – some may say a 'high-fidelity model'. The importance of modeling and simulation standards (such as NASA STD-7009) requiring verification and validation (V&V) tends to be down played because of our familiarity with and disposition to accept such computed results with limited scrutiny. Shortcuts or even side steps to V&V procedures are often taken due to schedule, cost, or staffing. However, as performance requirements increase and innovative structural concepts, materials, and fabrication processes are incorporated in the design, such confidence in current engineering analysis tools is eroding as the structural global response tends to be nonlinear and the local material response tends to involve multiple length scales. Specifically, our computational tools must now incorporate appropriate materials models that properly account for spatial dependencies (i.e., different material length scales) to develop the necessary understanding required to quantify design margin and flight risks and an awareness of when different material length scales are applicable. To understand the risk of failure, our computational tools must now incorporate capabilities to address a basic understanding of material performance (i.e., new material modeling tools to mimic observed local material behavior) and spatial dependence (i.e., inherent response dependencies across multiple material length scales). These two aspects are described further in the following sections.

4.2.1   Material Performance

FEMs are used to estimate the global structural system response and to extract the local deformation and stress states for use with a fracture mechanics tool, such as NASGRO® (Ref. 9). These computational models require using appropriate materials models that replicate global structural behavior associated with structural stiffness and deformations as well as attempting to mimic local material behavior associated with nonlinear local response, damage initiation, and damage propagation. In some cases, engineering practice has dictated developing a local model of a critical "hot spot" region using the same length-scale-independent continuum modeling approach to better define the local stress state. However, these material models ignore the physical basis of the material length scale dependencies.

Many finite element tools today use standard materials models based on conventional continuum theory and provide a single scalar stress metric, such as the effective stress using the von Mises assumption applied to ductile and isotropic materials behavior, to assess the local stress state. Local stress states are commonly anisotropic, rarely linear, and almost never characterized by a scalar quantity. A single scalar stress metric such as the von Mises stress, while convenient and common, is an inadequate metric for the local material behavior and its use can contribute to misinterpreting the true D&DT capability. Some finite element tools have been customized with

limited success using user-defined material models to address microstructural details within a CM framework. Unfortunately, applying these new material models requires significant validation effort for them to become new standard practice engineering tools, and when applied to an actual design, the resulting analysis model becomes computationally intractable using the current computational environment.

4.2.2   Spatial Dependence

Recognizing and accounting for spatial dependencies associated with the material as dictated by the design, by the fabrication or manufacturing process, or by microstructural tailoring for performance must be reflected in the materials model integrated within the modeling and analysis strategy whether it is a finite element approach or a new analysis paradigm. These material models provide a new class of computational tools that ensures accurate estimates of the local stresses for the appropriate material length scales (see Refs. 4-8). Capturing these local material spatial dependencies analytically becomes more and more critical with the need to estimate the local stress state at a different (smaller) material length scale than the standard practice FEM has the capacity to simulate. Furthermore, test data to validate such new material models are nearly non-existent. Validating the analysis modeling tools by test is needed to demonstrate analysis credibility and predictive capability. Such a process leads to identifying and understanding contributions to engineering risk thereby leading to more accurate uncertainty quantification.

If the specific design problem requires predicting local stresses, local spatial dependencies associated with the material length scales depicted in Appendix A must be considered. Examples of such local spatial dependencies are plasticity, anisotropy, multi-directional composite, local microstructure details, and other length-scale dependencies (see Ref. 1). As the region of interest becomes small, conventional continuum mechanics assumptions coupled with material properties obtained from specimen and coupon testing[13] may not be valid for local stress prediction due to voids, interfaces, and discrete changes in microstructure. More complex, non-traditional materials models are needed to simulate local material behavior needed to quantify the local state of stress. Attempts aimed at this technology gap are evident in Refs. 11 through 21. This understanding is critical to accurately assessing D&DT capability and design margins. However, such a material model of a local state may not be available or may not be computationally tractable using current engineering tools. As a result, engineering assumptions are made to use averaged or smeared 'apparent' material properties for both global and local response determination. These assumptions are infrequently challenged or revisited, but instead are often accepted as an accurate representation of the local stress state based on the local mesh refinement (i.e., the finite element size approaches the grain size).

As the spatial modeling features of the analysis model approach the characteristic dimensions of the material's microstructure, very complex local non-continuum material effects (e.g., discrete material anisotropy, discontinuities, grain boundaries and grain orientations) that influence local material properties must be considered. This consideration is to ensure that D&DT predictions are accurate rather than relying on models using empirically fit parameters. More often than not,

---

[13] Such properties would represent micro-structurally averaged or apparent homogeneous mechanical properties for the test coupon. These tests are used to characterize macro-scale material properties including directional dependencies associated with large-scale structural anisotropy, but are inadequate to characterize the ever-present small-scale material anisotropy (i.e., grain boundaries, dislocations).

material data for new material models at these length scales are not available. For example, bulk tensile properties measured by standard uniaxial tensile testing assume continuum behavior. Uniaxial tension testing provides the basic material input to most elastic-plastic material models available in today's engineering analysis tools. However, these uniaxial tensile test results may not be applicable to problems involving a multi-axial stress state – even though a refined finite element mesh can be developed and a von Mises stress calculated using point stress components. For example, local microstructure properties that govern plasticity-driven failure processes[14] may need to be considered to assess the D&DT capability accurately. Unfortunately, such analysis results tend to be interpreted as an accurate representation of the local stress state, when in fact it is simply an extraction of a local stress based on global material assumptions (i.e., homogeneity) that cloud the D&DT assessment.

4.3 Examples Illustrating Standard Engineering Practice D&DT Challenges

An increasing number of NESC D&DT assessments illustrate the importance of recognizing the improper use of conventional standard-practice engineering tools and the tendency for *blind acceptance* of their calculated results perhaps due to schedule, cost, lack of understanding, or a combination of these factors. The following examples are given to illustrate the reality of the situation. Details of these examples are in the cited documents, only findings and recommendations from these assessments are cited here to illustrate the issue and its recurring nature.

4.3.1 Example # 1 - D&DT of Composite Overwrapped Pressure Vessel (COPV) Metallic Liners

Human Exploration Programs and Science Programs are both currently using light[15] COPV's with 0.030- to 0.040-inch thick metallic liners. The ISS COPV inventory listing is shown in Appendix B with two having a liner thickness less than 0.046 inches. The Commercial Crew Program (CCP), the Orion Program, and Space Launch Systems Program are considering *light* COPV designs. In addition, robotic science mission programs are considering using *light* COPV metallic liners as thin as 0.010 inch on future robotic missions for the potential weight savings. This is understandable, but the presumed minimal weight savings is questionable given that the increased risk associated with using a thin-liner COPV design is unknown and unquantified. COPVs exhibit two primary risks: one associated with the metallic liner (discussed here as Example 1) and the other associated with the composite overwrap (discussed later as Example 5).

The risk associated with the thin metallic liners and the ability to predict the D&DT performance of the COPV liner is documented in Appendix C and its attachments. This appendix presents a series of technical questions that summarizes current unknowns relative to the use of *light* COPV designs for CCP systems and contributed to the release of NESC Technical Bulletin No. 16-02

---

[14] Plasticity-driven failure processes – as local component dimensions become small relative to defect size or microstructure attributes and local D&DT predictions are necessary, local material properties (non-continuum effects) must be considered. For example, anisotropy effects may indicate that brittle grain boundary fracture effects must be considered or the effect of welding has influenced local microstructure properties or stress state (weld induced residual stress). Also, as defects approach a surface boundary, the stress intensity factor field is affected so that the similitude assumption cited previously in Section 4.1 becomes non-applicable. Eventually, localized micromechanical damage processes may dominate the failure condition.

[15] The term "*light*" COPV is used herein for COPVs containing thin liners of thickness less than 0.060 inches. This white paper does not address liner designs with thicknesses equal to or greater than 0.060 inches. Rationale for liner thickness ≥ 0.060 inch is unknown other than a functional rationale related to design pressure.

titled "Damage Tolerance Life Issues in COPVs with Thin Liners." For example, current NDE inspection methods, prior to vessel autofrettage[16], consist of dye penetrant of the liner surface and X-ray volumetric inspection of the liner weld region. The typical "special" sensitive dye-penetrant method qualified per NASA-STD-5009 has a surface flaw detection limit of 0.050 inch long by 0.025 inch deep and X-ray inspection can detect a flaw of size 0.6t (where "t" is total material thickness the X-ray encounters). A few COPV vendors have implemented an improved "special" dye-penetrant method having a surface flaw detection limit of 0.030 inch long by 0.015-inch deep. For a 0.030-inch-thick liner, D&DT analysis thus assumes the metallic liner contains a remaining ligament size ranging from 0.005 inch to 0.015 inch using typical or best dye-penetrant methods, respectively. Understanding the growth kinetics of small flaws shown in Figure 4.1 is extremely complex and predicting the life of thin liner COPVs will require extensive work before it is achievable. Appendix X3 of ASTM E647-15 (Ref. 10) provides test method guidelines where small or short fatigue cracks control a significant fraction of the structural life.

Note: EP - Elastic Plastic fatigue crack growth
        LE – Linear Elastic fatigue crack growth
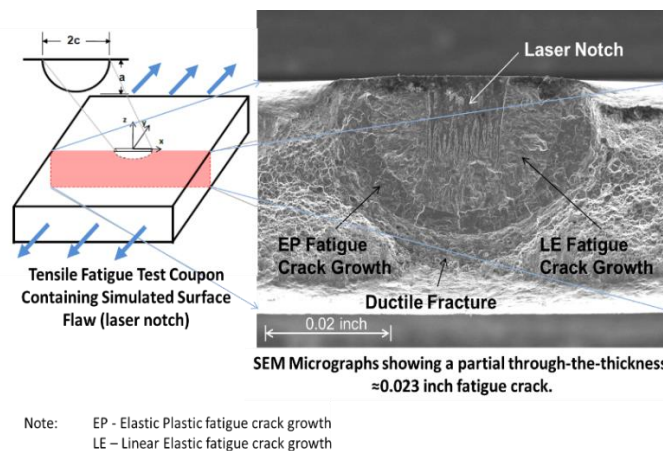
Figure 4.1. Test coupon results simulating the growth of a small surface flaw (crack) in a 0.032-inch-thick metallic liner. The scanning electron microscope (SEM) micrograph (right) shows the through-the-thickness fracture surface depicted (red cross-section) in the drawing (left). (Ref. 22)

Compounding the D&DT analysis is the fact that all liner flaw inspections occur prior to COPV autofrettage. In the autofrettage process, the metallic liner is plastically expanded into the composite overwrap. As a result of the liner expansion, a crack-like flaw contained in the liner can grow leaving a smaller remaining ligament that cannot be accounted for using conventional D&DT engineering tools because the remaining ligament is on the order of the grain size thereby violating continuum mechanics assumptions embodied in the existing tools. Such phenomena – cracks in yielded thin ligaments – are not unique to COPVs. In some cases, the influence of through-the-thickness plastic yielding is accounted for using a rule-of-thumb, or correction factor, on the LEFM solution; however, at certain length scales, such an approximation becomes inappropriate. Unfortunately, LEFM underlying assumptions are frequently misunderstood, misinterpreted, or possibly ignored.

---

[16] Autofrettage is a metal fabrication technique in which the assembled COPV is subjected to internal pressure that significantly exceeds the operating pressure, causing the metallic liner to yield plastically. Reducing the autofrettage pressure results in internal compressive residual stresses in the metallic liner and tensile residual stresses in the composite overwrap.

In addition, thin liners are susceptible to highly localized permanent deformations resulting from liner expansion (embossing the overwrap interior surface onto the liner exterior surface). Such deformation processes have the potential to create regions of strain localization and influence the liner response when the autofrettage pressure loading is removed since local liner buckling may develop contributing to liner/overwrap disbond. Because the remaining liner ligament can be small, the embossing effect can have a further harmful effect by resulting in ligament plastic collapse, which is unrelated to classical fracture failure mode. The current traditional engineering analysis paradigm (discussed in the preceding section) 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.

4.3.2 Example # 2 - Advanced Stirling Converter (ASC) Heater Head Fatigue/Crack Growth, April 2013, Tl-12-00829

New and innovative designs constantly require using small length scales to increase component efficiency. An example of how innovative designs push our ability to predict D&DT is the ASC heater head design. 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. Figure 4.2 shows that small (short) fatigue crack growth rates are accelerated compared to growth rates of long cracks. The NESC assessment concluded (Finding F-2) 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). 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 (Ref. 23) containing an understanding of the local damage processes depicted in Figure 4.3. It is important to note that using LEFM for this crack size to microstructure length scale does not meet the intent of standard practice of ASTM E647-15, Appendix X3.1 (Ref. 10).
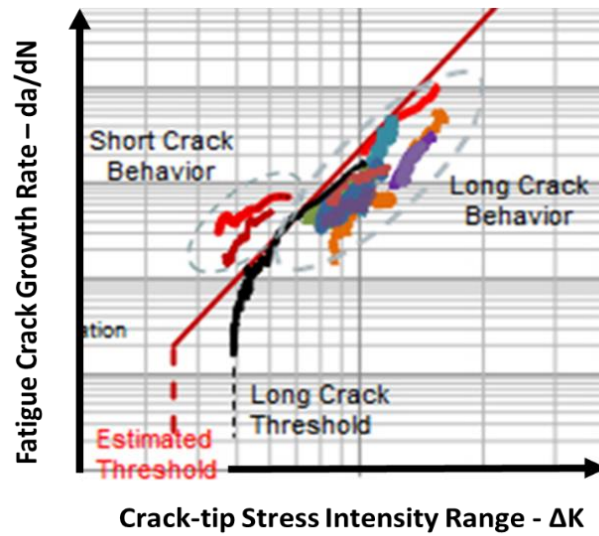
Figure 4.2. Comparison of fatigue crack growth rates for small (short) and long cracks where da/dN is the crack growth per loading cycle and ΔK is the difference between the maximum and minimum stress intensity factors.
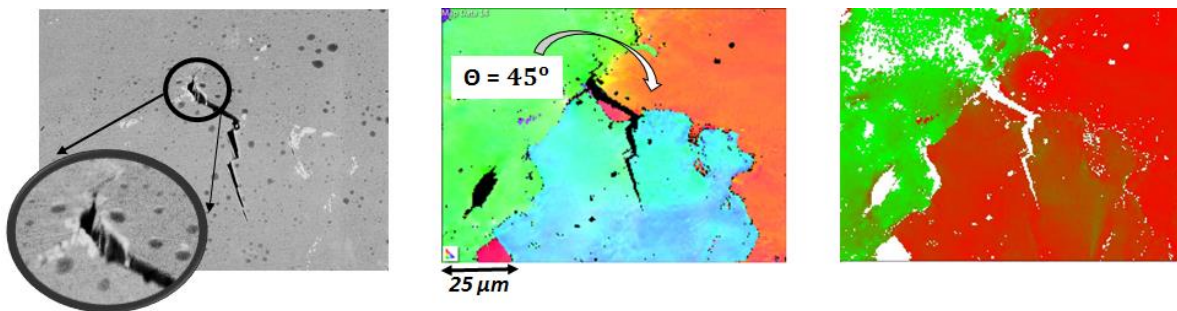
Figure 4.3a. Micrograph showing small fatigue crack that initiated within carbide inclusion and crack growth in large grains where Θ is the misorientation angle between two adjacent grains. The location of the carbide is shown using a circle (Ref. 23).
Note: 25μm ≈ 0.001 inch.
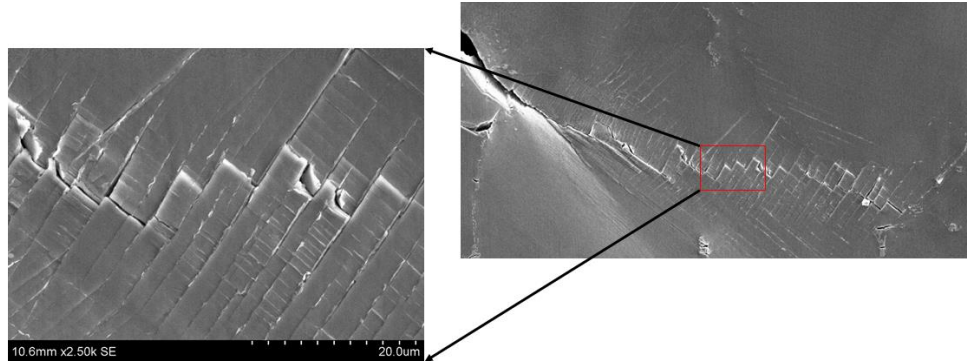
Figure 4.3b. Micrograph showing small fatigue crack morphology (complex slip-band cracking damage process) in large grain (average grain size = 75 μm, maximum grain size = 390 μm) (Ref. 23). Note: 25μm ≈ 0.001 inch.

4.3.3 Example #3 – Carbon/Carbon Silicon Carbide (C/C-SiC) – Material Characterization and Modeling – Phase II, May 2013, TI-11-00699

The NESC conducted an extensive three-phase technical assessment to determine whether a new complex high-temperature ceramic matrix composite for the pintle and pintle guide parts could be certified for use in the Orion launch abort system attitude control motor (see Refs. 24 and 25 for example). A primary objective of the NESC assessment was to understand the capability of the continuum-based modeling and analysis used to estimate design margin and investigate alternate modeling approaches to improve the predictive capability of the current continuum-based method. The NESC final recommendation was to not use the current continuum-based material modeling approach for analytically estimating design margin and to pursue a performance-based testing method that contributes to certification. The NESC found (Finding F-3, see Refs. 24 and 25) that while the continuum-based model may adequately estimate room-temperature break-test peak loads for specimens, it is not adequate to predict C/C-SiC pintle and pintle guide parts behavior during operation due to:

a. Limitation of linear-elastic shear stress-strain assumption contained in the continuum model.

b. Lack of local material modeling of a 4-directional composite system for local stress recovery relative to transverse isotropy assumptions for global response prediction (i.e., ignored local material length scales).

c. Lack of material properties over a range of elevated temperature that encompass operating temperature range.

d. Uncertainty that standard material property testing provided appropriate material characterization and damage modes.

e. Insufficient understanding of damage initiation and growth mechanisms.

f. Lack of analytical damage prediction models.

g. Insufficient understanding of the role of local microstructural features near strain concentrators (geometric features such as threads, notches, etc.).

h. Insufficient understanding of operating environments on material and structural responses.

The NESC further observed that accurate computation-based design margin for C/C-SiC pintle and pintle guide parts will be extremely difficult without a large uncertainty in the estimated design margin because of the following issues:

a. Complex loading environments (usually dynamic).
b. Strongly indeterminate or highly variable boundary conditions.
c. Poorly understood or variable material behavior.
d. Limited availability of C/C-SiC material with which to determine the required statistically based material property allowables.
e. Insufficient material property data at relevant elevated operating temperatures.
f. Significant uncertainties in the operating environments over the C/C-SiC pintle and pintle guide parts (non-uniformity of external local environments like temperatures, loads, pressures, both static and dynamic).
g. Lack of a verified materials model to calculate localized stresses and strains needed to estimate design margin determination.
h. Lack of validated stress or strain metric(s) to estimate performance (i.e., point values, values averaged over a unit-cell volume, von Mises effective stress metric).

When faced with similar computational limitations in determining design margin in the past, NASA has successfully relied on a comprehensive testing approach to show component reliability and robustness (refer to Ref. 24, paragraph 6.2 entitled A Review: Alternate Methodology for Establishing Structural Reliability). Such a testing program would:

a. Obtain a thorough understanding of the expected failure modes of the component through integrated analysis and testing, to include testing to failure to demonstrate that the component does fail as anticipated.
b. Demonstrate design robustness by qualification testing of components for durations longer than anticipated for worst-case operation, at greater than maximum expected operating conditions (e.g., loads, temperatures, pressures, etc.), and with known realistic defects, damage, or degraded sub-components.
c. Screen for production deficiencies by acceptance testing of each and every flight component under higher than nominal conditions adequate to expose detrimental flaws or degraded properties, but below excessive conditions that will induce damage in nominally acceptable components.
d. Utilize reliable NDE methods before and after all qualification and acceptance testing to detect any initial defects, the initiation of any new damage, and the propagation of detrimental damage conditions.

Although this approach has proven to be effective, such testing programs are very expensive and only apply to the specific material, structural configuration, and loadings considered. However, such programs do mitigate risk for the given design and application, thereby providing decision makers with credible performance assessment and guidelines. Just as inappropriate modeling and analysis pose potential hazards, so can a non-applicable test contribute to an inaccurate assessment. Diligence and technical rigor need to anchor our decisions and rationale for both testing and analysis.

4.3.4 Example #4 - STS-133/External Tank (ET)-137 Intertank (IT) Stringer Cracking Issue

During the filling of the ET-137 with cryogenic liquid fuels for the last mission of the Space Shuttle *Discovery* (STS-133), cracking in the foam on an IT panel near the liquid oxygen tank interface was observed (see Ref. 226). Upon further inspection, it was discovered that not only was the foam cracked, but also two external hat-shaped stringers under that foam on the IT had long cracks along the stringer feet between the fasteners and the stringer sidewall. Detailed three dimensional (3D) FEMs were developed and analyzed to investigate the stringer elastic-plastic response and to assess the potential for local failure to develop in the stringer feet.

Most structural materials contain some degree of anisotropy at the structural level (large or macro-level length scales) and/or at the material level (small material length scales). When understanding fracture-related performance is critical, materials models must represent both anisotropic behavior and material-specific failure mode attributes associated with multiple material length scales. For example, some material orientations are susceptible to strain localization based failure modes because of low fracture properties related to key microstructure features (small material length scales). This common failure mode is known to occur in composites and some monolithic metallic materials. In both cases, strain localization can occur at interfaces. In metallic materials, these interfaces are grain boundaries; and in composites, these interfaces are interlaminar (delaminations between lamina) or intralaminar cracking (delamination migration pathways through lamina). For these specific cases, strain is localized at the interface thus reducing fracture properties and/or fatigue life. These important material specific and anisotropic characteristics are extremely difficult to model analytically and to characterize by test across different material length scales and yet they are extremely important in assessing D&DT performance and understanding risk.

Most metallic sheet and plate products contain some degree of material anisotropy due to the fabrication, machining, and forming processes that is generally small. However, aluminum-lithium plate material can exhibit significant material length scale dependencies due to a high degree of anisotropy along with grain boundary strain localization effects. These complex material attributes influenced by fabrication and heat treatment cannot be suitably predicted using the conventional engineering analysis method discussed in Section 4.1 and material characterization testing is needed to support the design. Selecting an alternate material system is often based strictly on a weight-savings argument without understanding the potential risks being assumed if only limited test data are available.

Based on the detailed Space Shuttle ET IT stringer cracking assessment findings (Ref. 26), it was recommended (recommendation R-1) that aluminum-lithium alloy 2090 T8 sheet material should not have been used as a stringer material, because,

- The stringers can develop complex, localized through-the-thickness bending and shear stresses near the fasteners due to fabrication process, assembly loads, and combined mechanical and thermal loading.

- The through-the-thickness properties of alloy 2090 T8 are marginal (i.e., low ductility) and material processing variations, even within specification, can alter microstructural properties and unknowingly exacerbate cracking prior to ultimate strength under stringer local environments exhibiting bending and shear stresses.

At present, and again similar to the Space Shuttle ET IT stringer issue, the aft bulkhead of the Orion Exploration Flight Test (EFT-1) capsule, constructed of an aluminum lithium alloy, cracked during proof testing and is also an indication that current standard engineering practices have difficulty in predicting material local-property-related damage-tolerance performance and that previous recommendations are not lessons learned. Conversely, the analysis effort did not adequately represent the uncertainty in the predictions and did not account for these localized influencers (i.e., material length scale influences).

Unfortunately, in 1966, long before the Space Shuttle ET stringer issue, similar cracked stringer failures were noted, investigated and reported as a lesson learned in 1971 for the Saturn S-II-4 skin-stringer assembles built using 2020-T6 extrusions (Ref. 27). The final paragraph states: "*The major lesson learned from the 2020 cracking problem is that new materials require more than the usual specification verification tests for chemical and mechanical properties. Additional testing efforts must be expended to provide guidelines for satisfactory handing and fabrication procedures. Materials with adverse transverse properties should be especially suspect and signal a need for special attention.*" Apparently, it was a lesson not learned.

4.3.5 Example # 5 - D&DT of COPV Composite Overwrap

The second COPV primary risk is associated with the composite overwrap and the ability to predict composite damage and perform life assessment for the COPV (see Appendix C and Ref. 28). The composite overwrap carries a significant portion of the internal pressure loading imposed during autofrettage, proof testing, and operation. For space flight systems, these COPVs are deployed to achieve a long-term service life, with a situation for which there is minimal if any opportunity for inspection and repair. One failure mode is the stress rupture of the composite overwrap caused by local material failure of the fiber in tension. Such a failure involves multiple micromechanics effects including fiber failure, fiber/matrix interfacial failure, redistribution of local loads, and through-the-thickness damage mechanisms – all predominately small material length scale mechanisms, which exceeds our ability to observe or inspect. Although rare, such a failure after the COPV has been in service for a period of time is potentially catastrophic.

The NESC performed an assessment on carbon/epoxy stress rupture (Ref. 28) and found that the models typically used by industry for estimating the threat of stress rupture were not supported by an adequate set of experimental data and a comprehensive test program was recommended. Issues with complex pressure-time history, uncertainty treatment, stress ratio determination, and available data have not been adequately resolved in past modeling efforts. Current and future NASA programs rely on these data for estimates of COPV reliability, but these reliability estimates cannot be determined with confidence.

The interactions between the liner and the composite overwrap during fabrication and proof testing challenge the current engineering analysis tools in assessing potential defects, disbonds, inelastic response, and local imperfections. Further, the applicability of fiber failure models based on fiber strand tests have not been validated in an overwrap application where fiber strands and matrix interact, and local load paths develop. Reliance on industry design standards and historical COPV performance data provide the standard engineering practice to-date until validation tests are defined and performed and used to validate new analysis models at the appropriate material length scales. Such a validation approach was expressed by the alternate opinion in Ref. 25 and led to the following recommendation: "The failure mechanism(s)

underlying stress rupture of COPVs is not understood, and serves as the barrier to reliable predictive models and safe COPV operation. A mechanistic model of COPV stress rupture based on damage evolution data obtainable from transverse tensile tests has a greater likelihood than the proposed empirical approach for achieving a reliable predictive capability, and in a shorter time and at much lower cost."

4.3.6 Example #6 -- Pluto New Horizon Launch Vehicle Tank Qualification Test Failure; Final Report, Vol. I, NESC Report RP-06-02-05176, 08-28-2008

This qualification test failure was attributed to a failure at the end of a stiffener flange near an attachment point. Finding F-3 states that the structural analysis and margin assessment were incomplete. The global FEMs were unable to properly model or converge when the anisotropic elasto-plastic material properties of the tank were considered. Local spatial dependencies included local changes in curvature, presence of loaded bolt hole, and changes related to stiffener termination. Since the directional dependency of the material properties at multiple material length scales (macro and micro) was an essential part of the crack initiation, propagation, and rupture process, the inability of the analysis model to converge numerically meant the qualification test failure could not have been predicted by the global model, but also that the global model could not be used to determine the capability to withstand the expected ground processing and flight loads related to the Pluto/New Horizons mission. Local analysis models were formed from a subset of the global FEM (i.e., using a global-local approach) and were able to converge numerically. However, these local models were based on the same material modeling approach as used in the global model and hence, their results were similarly limited in the modeling of the anisotropic nonlinear material behavior at the appropriate material length scale. Consequently, their results could not be relied upon to determine the actual stress state of the material in the region of failure where small material length scales influence the response.

4.3.7 Other Examples

Other examples from previous NESC assessments can be cited to illustrate this issue and its pervasive nature throughout the Agency, and in some respects, throughout the broader aerospace industry. These additional examples where multiple material length scales are involved include:

- Reentry thermal protection system – limited material data, complex local multi-physics environments, lack of fiber bridging material modeling, lack of fracture data for substrate, coating and interface conditions, coating spallation. See Ref. 29.

- Margin assessment of adhesive joints for electronic components – lack of material property data, lack of material model through a glass transition region, reliance on linear elastic stress analysis results within a nonlinear material response regime.

- Margin assessments for nonlinear systems using ratios of analysis results in lieu of a material allowable and over reliance of solid-geometry-based finite element meshes as 'high-fidelity modeling' – meshing and modeling are intrinsically different.

- Using LEFM for non-homogeneous, nonlinear closed-cell foams assuming a linear elastic, homogeneous, continuum-like material response (see Figure A-5 of Ref. 30).

- Characterizing new materials and the supporting analyses based on limited material availability, conventional continuum mechanics assumptions, and uncertainty in environments and loads resulting in severe consequences if failure occurs.

- Increased dependency on material length scale for advanced manufacturing techniques compared to traditional material processing and fabrication. Changes in damage mechanisms and growth for additive manufacturing processes. Developing appropriate material models for new fabrication and manufacturing processes.

- Propulsion valve bellows seals must carry pressure loads as reliably as other pressurized propulsion system components including tanks (metallic or COPV), pipes, and valve bodies. To meet valve design criteria, the bellows are often hydro-formed (plastically deformed) from multi-ply, thin-wall tubing material where the through-thickness dimension is on the order of the metallic grain size. Valid through-thickness material properties, damage-tolerance prediction methods, and certified non-destructive inspection techniques do not exist to evaluate or certify these fracture critical components for flight.

In some cases, lack of or limited material data was the primary issue; in other cases, there was a reliance on existing methods because of Engineering familiarity and possibly schedule or cost pressure. However, the real culprit is our inability or unwillingness to acknowledge and accept limitations in our understanding and our desire to develop an engineering solution even if it may be inappropriate. Often, in these cases, we have been protected from ourselves because of previous mandated factors of safety. Thus, as we extend these designs and life-extension predictions are made, we unknowingly may be increasing risk causing the unknown unknowns to become critical players in the D&DT evaluation.

Because of Agency funding constraints, it has become increasingly apparent that Engineering may be over relying on existing computational methods driven in part by their ease of use and the availability of significant computing power to solve large-scale finite element meshes. However, the Agency needs to develop a sufficient technical understanding of the capability and limitations of these tools by conducting thorough testing and by proactively developing advanced engineering computational tools with validated predictive capabilities for anticipated advances in materials and design capabilities. The current design environment and engineering practice for high-risk missions involving severe or even hostile environments require a new level of accountability on the analyst to understand the technical basis of the tools, their assumptions, their limitations, and their applicability to the current design problem across multiple material length scales.

5.0   Needs and Recommendations

This report has identified several deficiencies in the Agency's standard Engineering practice related to D&DT and provided examples from previous NESC assessments that illustrate the need for re-tooling. Three needs have been identified and are described in the following sections followed by a list of recommendations.

5.1   Understanding the Limits of Engineering Methods

An important weakness in the Agency's ability to develop new technologies lies within our ability to conduct proper trade studies. As new missions are formulated and advanced human space flight vehicles are developed, Engineering must also understand the limits of its predictive tools; in particular, those used for trade studies. Traditionally, trade studies have been performed using rapid design tools with system-level requirements without acknowledging and accounting for potential influences of D&DT that may redirect a trade study. Engineering must ask the difficult questions like, can we predict the D&DT capability of inflatable habitats? How long

can we safely operate vehicles in deep space? Do we need new predictive tools for advanced materials and advanced manufacturing? Many other questions can and should be asked. For safe human deep space travel, the Agency cannot rely on the current LEO reliability method that is based primarily on repair and rapid/reliable return to earth. As the Agency moves toward long-duration, deep-space, human exploration, the D&DT engineering approach must be able to be proactive and develop new tools where vulnerabilities are as yet unidentified, but critical for mission success. Such an approach is anticipated to require a workforce having a different skill set that asks the difficult questions, challenges conventional wisdom, and pursues technical rigor above all.

5.2   Need for Advanced Engineering Computational Tools

The erosion of the Agency's engineering D&DT computational capability has not occurred over night. The examples listed in the previous sections show that the engineering community has had difficulty in developing rigorous understanding and methods to assess risk when complex material modeling issues were not recognized, understood, or addressed properly. These difficulties will be compounded as designs require a multi-physics modeling approach (e.g., the frangible joint assessment, additive manufacturing, and multifunctional materials). The Agency has reached a point where new spacecraft design requirements have made our D&DT predictive capabilities obsolete in areas when an understanding of complex materials and local environments is required. The Agency's engineering and research communities have understood our weaknesses for many years and have proposed solutions based on new CM and multi-physics based technologies to develop advanced engineering predictive D&DT tools (see Appendix D). Nearly four years have passed since the Fundamental Engineering Sciences initiative and advanced computational-materials-based methods were proposed to address vulnerable engineering D&DT practices. The Agency must become proactive and develop new predictive engineering tools applicable to emerging material systems and manufacturing technologies to ensure safe, deep-space, human and robotic exploration and interplanetary habitation. The Agency needs to learn the lesson from Saturn (Ref. 24) that "*new materials require more than the usual specification verification tests for chemical and mechanical properties.*"

5.3   Validation Testing Needs

With Agency funding constraints, it has become increasingly apparent that engineering may be overly reliant on existing analysis methods and not developing a sufficient technical understanding by conducting a thorough testing approach including sufficient replicas to understand variability. Validation tests generate data for the purpose of model validation and are defined and developed through cooperative and collaborative efforts between the test engineer and the analyst – usually they are different individuals. A series of such validation tests may be performed as the design progresses through a building-block development process (i.e., replica tests, and/or specific feature tests). Through the verification and validation (V&V) process, a model can be declared "validated for its intended use" once it has met the validation requirements. These requirements are established in the V&V plan and often include descriptions of specific tests that need to be run or other referents (i.e., data, theory or information) that need to be gathered, what specific measurements need to be acquired from the tests and accuracy statements about the agreement between simulation outcomes and experimental/test outcomes, as discussed in Appendix E.

Because of the complexities associated with local environments that drive important small length-scale damage processes and their influence on D&DT, standard test methods often do not capture the proper and complete understanding required to develop material models reflecting multiple length scales. New test methods must be developed and introduced into the standard engineering practice to verify and validate complex D&DT analysis findings. New NDE inspection techniques must be developed and validated to ensure structural integrity and to characterize the local material state and its evolution as the environments and operational loads are imposed.

5.4   Recommendations

The recognition of the need for and pursuit of advanced engineering practices related to new exploration missions is a critical step to ensure that each Agency technical discipline is prepared for the future. The Agency must acknowledge that new standard engineering practices are required to exploit the emerging materials, fabrication techniques, and design configurations needed to meet the life-performance requirements placed on new spacecraft system. This is especially true for human exploration missions. Mission success and safety require technical rigor across multiple material length scales when assessing D&DT. A multi-discipline CM based effort is recommended with the Materials Technical Discipline Team (MTDT) having the lead with active participation and collaboration with both the Structures TDT and the NDE TDT. It is recommended that this effort include the following items as a starting point.

- Provide significant and sustained funding for Agency-sponsored CM research and development leading to a re-tooling of the D&DT standard engineering practice.

- Generate a report cataloging the current state-of-the-art of CM engineering across the aerospace community, especially within the Agency. This report should identify potential partners from other government agencies, in particular the DoE and DoD, for developing integrated computational material engineering (ICME) and to foster interagency communication and technical exchange.

- Establish an NESC multidisciplinary team (MTDT led with Structures and NDE TDTs) to develop CM-based engineering D&DT test and computational methods. Exploit the NESC leadership structure and technical focus in providing oversight and accountability. The following recommendations should be focused on specific material systems, fabrication techniques, and local environments important to the Agency for future spaceflight missions.

- Establish a work effort to address near-term thin-liner D&DT issues associated with lightweight COPV methodology needs. These needs will likely include validation testing (properties, component and NDE test development) and computational methods development.

- Establish a work effort to identify D&DT needs and issues associated with components fabricated using additive manufacturing techniques. These needs will likely include validation testing (properties, component and NDE test development) and computational tools development.

- Develop testing procedures and techniques to generate test data to validate new D&DT strategies and procedures focused on small material length scales.

- Assess the current and develop new NDE capabilities to support validation testing focused on small material length scales.

- Develop and implement new standard engineering practice D&DT guidelines and tools applicable across multiple material length scales for the future aerospace systems.

- Increase awareness of material length-scale influences on D&DT related to standard engineering practices using a workshop/forum/NESC academy approach.

- Educate the Agency workforce regarding material length scales and their impact on D&DT assessments and the potential limitations of the standard engineering practice using a short-course format.

6.0   Concluding Remarks

With our increased reliance on analysis methods to assess designs, it is critical that we recognize the potential shortcomings of our current standard Engineering practice tool set and the need to re-tool. This re-tooling process involves developing an understanding of the input data requirements of the computational tools, recognizing the limitations of current computational tools, developing the appropriate tests to conduct where important understanding is needed to validate the computational tools, and investing in new engineering tools that will be needed for new designs, new materials, and/or new fabrication processes to meet the ever-increasing demands of more ambitious space exploration. Since Engineering likely spends most of their time under the gun to produce new designs under cost and schedule constraints, they likely do not have the time or motivation to stay abreast of the new advancements in technology that will be required. Sustained investments in skilled people placed in a cooperative environment where multidisciplinary R&D can be pursued is what is critically needed for progress in these areas – including elements of advanced computational methods, micro- and meso-mechanical modeling, materials science, and advanced experimental methods. Only in such an environment can physics-based micro-mechanics and meso-mechanics analytical models be integrated with large-scale computational capabilities, and rigorously validated. To make progress on a reasonable time scale, NASA's multidisciplinary team and Agency-wide capabilities need to be linked, either formally or informally, to capabilities that exist at selected universities and research institutes to effectively incorporate the underlying micro-mechanical and meso-mechanical analytical modeling that needs to be developed and applied. Such physics-based modeling is required to achieve the understanding that is cited throughout this report.

In addition, the Agency must take a reasonable/realistic view of new designs relative to current engineering analytical capability and limit challenging designs either when appropriate computational tools are not available or not verified, or when limited amounts of material and/or parts are available to understand mechanical and thermal response, or when uncertainties with regard to bounding environments are high. Otherwise, the Agency must invest in developing a more thorough testing approach to mitigate the risk associated with the lack of knowledge and understanding for a given design and mission and to acknowledge the limitations of the computational tools to solve all problems.

7.0   References

1. Krupp, U., *Fatigue Crack Propagation in Metals and Alloys: Microstructural Aspects and Modeling Concepts*, John Wiley & Sons, 2007.

2. Davidson, D.L., "How Fatigue Cracks Grow, Interact with Microstructure, and Lose Similitude," *Fatigue and Fracture Mechanics: 27th Volume*, American Society for Testing and Materials, ASTM STP 1296, R.S. Piascik, J.C. Newman, and N.E. Dowling, Eds., 1997, pp. 287-300.

3. Ritchie R.O. and Suresh S., "The Fracture Mechanics Similitude Concept: Questions Concerning Its Application to the Behavior of Short Fatigue Cracks," *Letter, Materials Science and Engineering*, 57 1983 L27-L30.

4. *Fatigue and Microstructure, Papers presented at the 1978 ASM Materials Science Seminar*, American Society for Metals, Metals Park, OH, 1979.

5. Ritchie, R.O. and Lankford, Eds., *Small Fatigue Cracks,* Proceeding of the Second Engineering Foundation International Conference / Workshop, The Metallurgical Society, Inc., Warrendale, PA, 1986.

6. Starke, E.A. Jr. and Williams, J.C., *Microstructure and Fracture Mechanics of Fatigue Crack Propagation,* Fracture Mechanics: Perspectives and Directions, 20th Volume, ASTM STP 1020, R.P. Wei and R.P. Gangloff, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 184-205.

7. Needleman, A., *Computational Mechanics at the Mesoscale*, Acta Metallurgical, 48, 2000.

8. Van der Giessen, E. and Needleman, A., *Micromechanics Simulations of Fracture*, Annual Reviews Material Research 2002, 32, pp. 141-162.

9. NASGRO Fracture Mechanics and Fatigue Crack Growth Analysis Software, Version 8.1, Southwest Research Institute, San Antonio, TX, May 16, 2016.

10. ASTM Standard E647-15, Standard Test Method for Measurement of Fatigue Crack Growth Rates, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 2016.

11. Glaessgen, E. H., Phillips, D. R., Yamakov, V., and Saether, E., "Multiscale Modeling for the Analysis of Grain-Scale Fracture within Aluminum Microstructures," AIAA Paper No. 2005-1851, April 2005.

12. Gates, T. S., Odegard, G. M., Frankland, S. J. V., and Clancy, T. C., "Computational Materials: Multi-scale Modeling and Simulation of Nanostructured Materials," *Composite Science and Technology*, Vol. 65, pp. 2416-2434, 2005.

13. Anon., *Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security*, National Research Council, 2008.

14. Bednarcyk, B. A. and Arnold, S. M., *A Multiscale, Nonlinear, Modeling Framework Enabling the Design and Analysis of Composite Materials and Structures*, NASA TM-2012-217244, February 2012.

15. Glaessgen, E. H. and Stargel, D. S., "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles," AIAA Paper No. 2012-1818, April 2012.

16. Pineda, E. J., Bednarcyk, B. A., and Arnold, S. M., "Achieving ICME with Multiscale Modeling: The Effects of Constituent Properties and Processing on the Performance of Laminated Polymer Matrix Composite Structures," AIAA Paper No. 2014-0461, January 2014.

17. Engelstad, S. P., Koon, R. W., Action, J. E., Riga, J. M., Waas, A. M., Robbins, D., Dalgarno, R. W., Aarfath, A. R., and Poursartip, A., "Integrated Computational Materials Engineering for Airframe Composite Structure Applications," AIAA Paper No. 2014-0198, January 2014.

18. Talreja, R., "Assessment of the Fundamental of Failure Theories for Composite Materials," *Composite Science and Technology*, Vol. 105, pp. 190-201, 2014.

19. Saether, E., Hochhalter, J. D., Glaessgen, E. H., and Mishin, Y., *Multiscale Analysis of Structurally-Graded Microstructures Using Molecular Dynamics, Discrete Dislocation Dynamics and Continuum Crystal Plasticity*, NASA TM 2014-218265, May 2014.

20. Anon., Modeling Across Scales: A Roadmapping Study for Connecting Materials Models and Simulations Across Length and Time Scales, The Minerals, Metals and Materials Society (TMS), 2015.

21. Moghaddam, M. G., Achuthan, A., Bednarcyk, B. A., Arnold, S. M., and Pineda, E. J., "A Multiscale Computational Model Combining a Single Crystal Plasticity Constitutive Model with the Generalized Method of Cells (GMC) for Metallic Polycrystals," Materials, Vol. 9, May 2016, article number 335.

22. Piascik, R.S., *Fracture Mechanics Based Methods Development for COPV's with Metallic Liners*, NESC-RP-06-065, July 2010.

23. Yeratapally, S. R., Hochhalter, J. D., Ruggles, T. J., and Saigid, M. D., *Investigation of Fatigue Crack Initiation and Growth in Cast MAR-M247 Subject to Low Cycle Fatigue at Room Temperature*, To be Published in the International Journal of Fracture, 2017.

24. Piascik, R. S., *Carbon-Carbon Silicon Carbide (C/C-SiC) - Material Characterization and Modeling – Phase II*, NASA/TM-2013-218020/Volume I, July 2013.

25. Piascik, R. S., *Carbon-Carbon Silicon Carbide (C/C-SiC) - Material Characterization and Modeling – Phase II: Appendices*, NASA/TM-2013-218020/Volume II, Parts 1, 2, and 3, July 2013.

26. Piascik, R.S., *Space Transportation System (STS)-133/External Tank (ET) Intertank (IT) Stringer Cracking Issue and Repair Assessment: Proximate Cause Determination and Material Characterization Study*, NESC-RP-10-00680, Sept. 2011.

27. Anon., *Saturn S-II Problem Resolution History Report*, North American Rockwell Space Division Report SD 71-256, September 1971.

28. Prosser, W. H., Raju, I. S., and Piascik, R. S., *Composite Pressure Vessel Working Group (CPVWG) Task 3: Stress Rupture Test Approach*, NASA TM-2012-217564 (NESC-RP-09-00537), April 2012.

29. Kerr, J. H. and Cragg, C. H., *Likely Mechanism and Contributors to the Root Cause for Orbiter Wing-Leading-Edge Joggle RCC SiC Coating Spallation*, NASA TN-2011-217312, December 2011.

30. Sullivan, R. M., Lerch, B. A., Rogers, P. R., and Sparks, J. S., "An Overview of Spray-On Foam Insulation Applications on the Space Shuttle's External Tank: Foam Applications and Foam Shedding Mechanisms," presented at the 43rd Annual Technical Meeting of the Society of Engineering Science, August 2006.

31. Mishnaevsky, L., *Computational Mesomechanics of Composites*, John Wiley & Sons, 2007.

32. Miller, K. J., "The Three Thresholds for Fatigue Crack Propagation," *Fatigue and Fracture Mechanics: 27th Volume*, American Society for Testing and Materials, ASTM STP 1296, R.S. Piascik, J.C. Newman, and N.E. Dowling, Eds. 1997, pp. 267-286.

33. MIL-HDBK-17-3F, Figure 5.4.6.1 on p. 5-62 and Figure 5.4.6.2 on p. 5-64.

34. Communications with Dr. James Reeder, NASA LaRC.

Appendix A: Material Length Scale Description

Various definitions have been given for the various material length scales as they relate to mechanical design [13]. Following the definitions of Mishnaevsky [31], macro-scale refers to a specimen of coupon or structural element or even vehicle level analysis model where the length scale is on the order of more than a millimeter. Material response at this level is analyzed using conventional continuum mechanics and loosely defined as the structures discipline. Micro-scale refers to a microstructural level on the order between 1 micrometer and 1 millimeter. Material behavior at this scale falls into the area of material science, and is analyzed using methods of both physics and mechanics of materials, including micromechanics and fracture mechanics. Loosely defined, this scale is the materials discipline. Nano- and atomistic scales are less than 1 micrometer. Material behavior at this scale falls into the area of the physics of the materials and is loosely defined as basic physics.
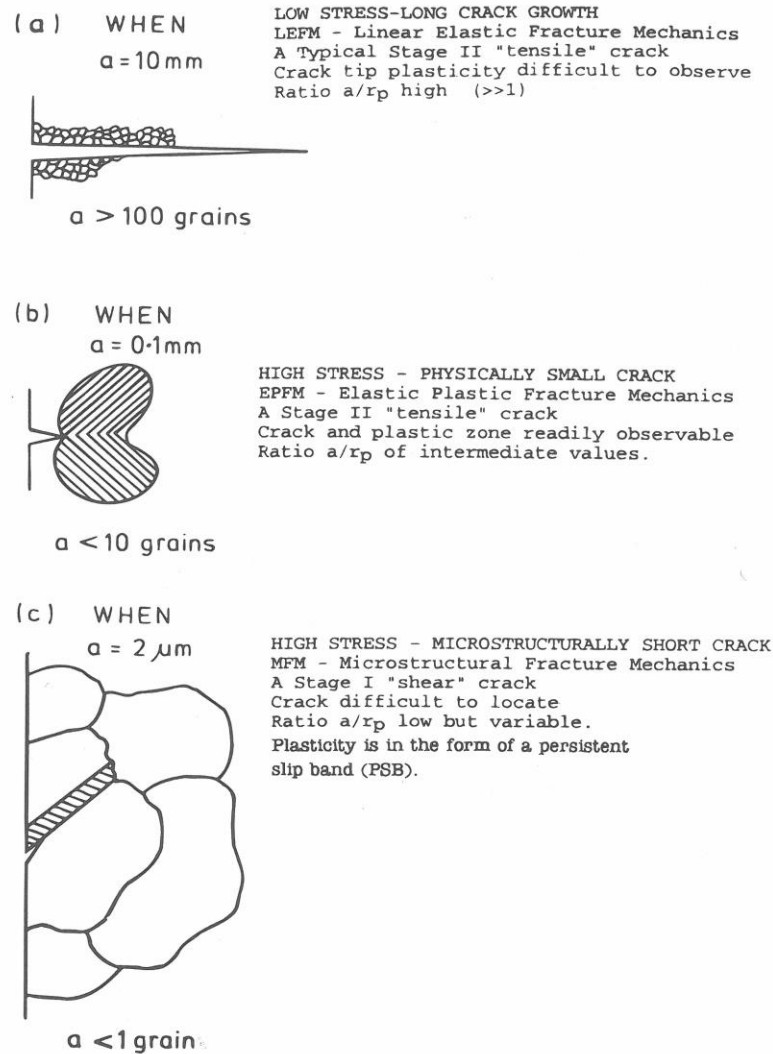
Micro-scale models essentially imply that nano-scale effects do not need to be considered. Likewise, macro-scale models assume that microstructure effects do not need to be considered. In all cases, finite element techniques have been and are being used to solve the various partial differential equations associated with the fundamental conservation laws.

In addition, some researchers use the term "meso-scale" to signify a scale "in between" any two of the three previously mentioned scales. Herein, meso-mechanics studies quantitatively the interaction and synergistic effects of many elements of microstructures (as inclusions, voids, shear bands, microcracks – general heterogeneity of the material) on strength and mechanical properties of materials. Mesoscale, per Needleman [7], then defines an intermediate scale between direct atomistic and an unstructured continuum description of deformation processes. While the meso-scale definition is somewhat arbitrary, meso-scale representations typically consider some aspects of both discrete and continuum influences (e.g., discrete dislocation plasticity where dislocations are explicitly simulated within a localized homogenized elastic continua).

Consequently, various mechanics formulations provide a roadmap to address different material length scales and their underlying assumptions. Understanding the different length scales and selecting the appropriate mechanics formulation validated by test is crucial in developing advanced CM models (see Refs. 13 and 31). Evolving such science-based CM tools into engineering D&DT tools that are adopted as standard practice will need emphasis.

The following figures depict critical length scale features related to crack growth in metallic materials (see Figure A-1) and important features that control damage in laminate composite materials (see Figures A-2 through A-4). The anisotropic nature of a foam's microstructure is shown in Figure A-5. These figures are provided to indicate the importance of material length scales for different material forms under some characteristic length scale associated with a material feature at some level. These examples illustrate the local complexities and imply their increase as local environments become multi-dimensional.

Example: Metallic Materials

(a) WHEN
a = 10 mm

LOW STRESS-LONG CRACK GROWTH
LEFM - Linear Elastic Fracture Mechanics
A Typical Stage II "tensile" crack
Crack tip plasticity difficult to observe
Ratio a/r_p high (>>1)

a > 100 grains

(b) WHEN
a = 0·1mm

HIGH STRESS - PHYSICALLY SMALL CRACK
EPFM - Elastic Plastic Fracture Mechanics
A Stage II "tensile" crack
Crack and plastic zone readily observable
Ratio a/r_p of intermediate values.

a < 10 grains

(c) WHEN
a = 2 μm

HIGH STRESS - MICROSTRUCTURALLY SHORT CRACK
MFM - Microstructural Fracture Mechanics
A Stage I "shear" crack
Crack difficult to locate
Ratio a/r_p low but variable.
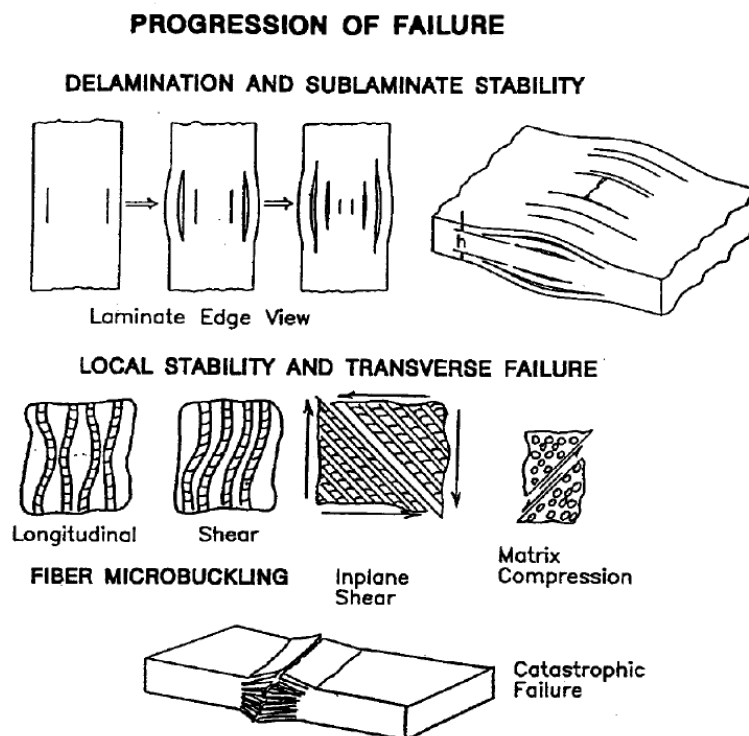Plasticity is in the form of a persistent
slip band (PSB).

a < 1 grain

Figure A-1. Three regimes of fracture mechanics with crack sizes given in relation to the material grain size, and the ratio of crack size to plastic zone size, a/r_p: (a) LEFM, (b) EPFM and (c) MFM, Ref. 32.

Example: Laminate Composite Materials

PROGRESSION OF FAILURE

MATRIX DAMAGE ACCUMALATION AND INTERACTION
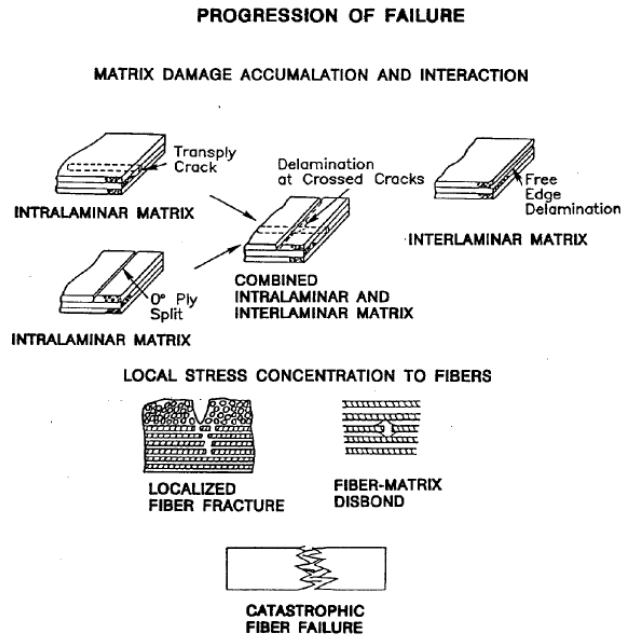
Figure A-2. Failure mechanisms for laminates loaded in tension, Ref. 33.

PROGRESSION OF FAILURE

DELAMINATION AND SUBLAMINATE STABILITY

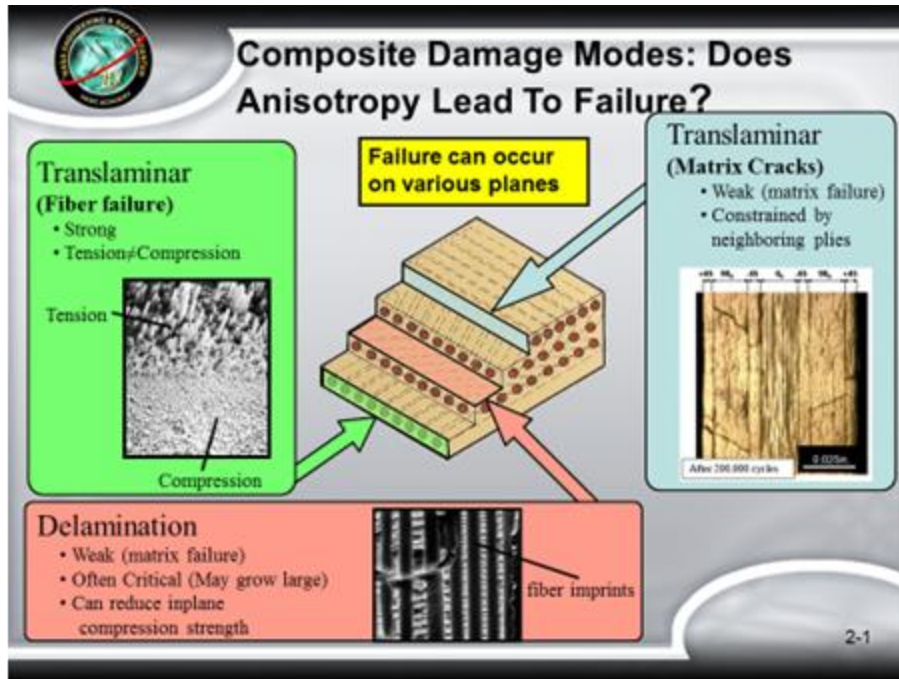
Figure A-3. Failure mechanisms for laminates loaded in compression, Ref. 33.

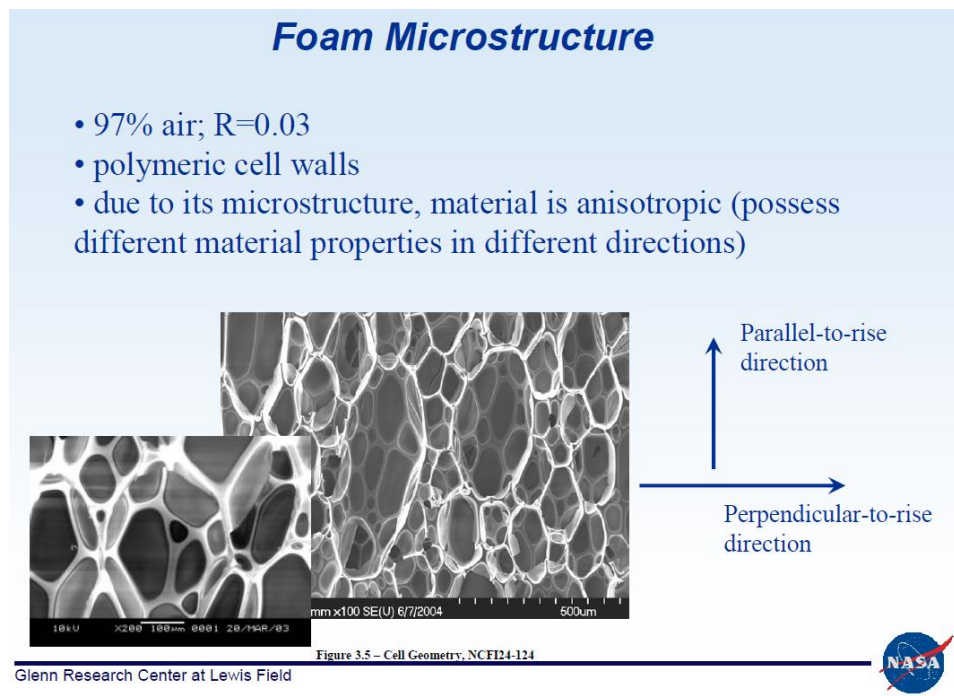*Figure A-4. Important micro-scale defects that influence damage modes, Ref. 34.*

Figure A-5. Foam anisotropic microstructure, Ref. 30.

Appendix B: ISS COPV Listing

Per Communications: Email (Attachment), Subject: ISS COPV Listing, From: L. Grimes-Ledesma, To: R. Piascik, C.C.: M. Kirsch, dated 6-6-2016.

Name	MFG	Pressurant	Part #	Type	Dia (inch)	Length (inch)	Liner Material	Liner Thickness	MEOP
ISS PCA (HPGT)	Arde	O2 or N2	D4467	Spherical	37.9		Cryoformed 301	0.093	3400
ISS Safer II	Arde	O2 or N2	D4616	Cylindrical	6.56	8.93	Annealed 304L	0.05	10,000
ISS NTA	GD	N2	1F96201	Cylindrical	19.7	45.23	6061-T6	0.05	3000
ISS CIPAA	Cobham			Cylindrical	4.4	9.64	6061-T6	0.07	4500
ISS PCU	Arde	Xe	D4636	Spherical	15.35		Cryoformed 301	0.03	3000
ISS BTF	SCI		1273084	Cylindrical	4.4	12.1	6061-T6	?	3000
STS MPS	Arde	He	D4554	Spherical	26		Cryoformed 301	0.046	4500
AMS-2 (Xe)		Xe, He, or CO2							
VCAM		He							
GBU (CO2)		CO2, He, or Ar							
GBA		Ar							
VGA		Air							
SpaceDRUMS									

Appendix C: Review - Variance to Reduce COPV Proof Factor from 1.50 to 1.25

R. Piascik (February 10, 2016)

Based upon a request from Tim Wilson (Director, NESC), a rapid review was conducted to understand the technical rationale that justifies a composite overwrapped pressure vessel (COPV) proof factor reduction from 1.5 to 1.25 prompted by a variance request.

Background:

[A] Company is building carbon-fiber overwrapped COPVs that meets their current requirement of 2.0 burst factor and 1.5 proof test factor for all human spaceflight applications per NASA STD 5019 (see Attachment 1) and ANSI/AIAA S-081A (see Attachment 2). [A company] has requested a variance on the NASA STD 5019 proof test factor requirement to allow for a reduction in proof factor from 1.5 to 1.25 in accordance with JSC 65828, refer to Attachment 3.

NOTE: NASA STD 5019 paragraph 4.1.2.1.3 states that COPVs shall comply with the latest revision of ANSI/AIAA Standard S-081, refer to Attachment 1. ANSI/AIAA S-081A paragraph 5.1.2 states COPV's shall be proof tested to a minimum pressure of: $P = \frac{1}{2}(1 + \text{Burst Factor}) \times \text{MEOP}$ (for a burst factor less than 2.0) or $= 1.5 \times \text{MEOP}$ for a burst factor equal to or greater than 2.0, refer to Attachment 2. (MEOP = [Maximum Design Pressure] (MDP) per the requirement of NASA STD 5019).

Discussion:

The following is a list of questions directed at specific issues associated with developing a rationale for lowering the proof pressure requirement from 1.5 to 1.25.

1. JSC 65828, Attachment 3, contains the proof pressure requirement of 1.25. **What is the technical rationale for the JSC 65828 requirement for a 1.25 proof pressure limit?** This is an important question because JSC 65828 is a primary document (standard) that allows the reduced proof which is in conflict with the governing NASA STD 5019 standard for fracture control of spaceflight hardware. The NASA STD 5019 requires COPV's to meet ANSI/AIAA S-081-2000 and therefore all COPV's with a design burst factor of 2.0 must meet the proof pressure requirement of 1.5.

   Based on discussions with L. Grimes-Ledesma and Ivatury Raju, the JSC 65828 proof test requirement evolved in 2006 from the Constellation Program (SDVR CxP 70135) who lowered the 1.50 proof test factor for COPVs to 1.25. A listing of the Programs that use a proof test factor is shown in charts entitled "Composite Overwrapped Pressure Vessel Proof and Burst Factor Analysis Result" by Nathanael Greene, JSC ES Pressure Systems/Fracture Technical Discipline Lead, Document 02032016, January 3, 2016. The discussions revealed that proof test factor reduction was based on concerns for composite overwrap damage caused by autofrettage. Note: Autofrettage is a sizing pressure operation where pressure driven deflection is used to plastically yield the metal liner into the overlying composite in order to induce initial stress states in the metal liner and composite. The autofrettage parameters are governed by the proof pressure factor. Therefore, a proof pressure factor of 1.5 will have a higher autofrettage sizing pressure than a proof factor of 1.25. The higher autofrettage sizing pressure mandated by

the 1.5 proof pressure factor is the root of the concern for composite overwrap damage from the stress rupture reliability calculations.

In addition, the Nathanael Greene charts suggest a potential conflict between NASA Structures requirements and NASA Fracture Control requirements (Chart 2). Chart 4 indicates that non-conformance requests are prevalent. While the pressure vessel standards and fracture control requirements have not changed, the structures requirement changed from 1.5 to 1.25 proof test factor (Chart 6). However, technical rationale for the proof test factor reduction has not been identified in this review.

2. **What data suggests a 1.5 proof pressure factor produces unacceptable composite damage?**
   As part of addressing this question, understanding of past history because the entire space COPV community has used and continues to use the existing ANSI/AIAA S-081-2000 requirement of 1.5 proof pressure factor. The 1.5 proof pressure factor has been used since 1984. No historical insight (data) has been given relative to the experience of using the 1.5 value. It is therefore presumed that no significant operational or manufacturing issues have negated its use of 1.5 proof pressure factor as an industry-wide requirement.

   The JSC 65828 document is a primary structures standard that requires all COPV to have a design burst pressure of 2.0 and a proof pressure factor of 1.25. The rationale for the lower 1.25 proof factor is based on stress rupture concerns during autofrettage as calculated by a carbon fiber breakage model. The model calculates a fiber strain value that approaches ultimate strength for a 1.5 proof factor based autofrettage. The fiber strain calculation suggests that autofrettage could produce unacceptable fiber damage leading to a reduction in stress rupture life and decreased reliability. The NESC has and continues to investigate the fiber breakage model; the model has not been validated by test and has been characterized by an NESC finding as having "significant shortcomings," per NASA/TM-2012-217564 (NESC-RP-09-00537). It is also worthy to quote the alternate opinion published in this NESC document; "Bottom line: The failure mechanism(s) underlying stress rupture of COPVs is not understood and that is the barrier to reliable predictive models and safe COPV operation."

   Other concerns have also surfaced relative to metallic liner pressure produced strain during a 1.5 proof pressure derived autofrettage. It is thought that excessive autofrettage tensile and compressive strain could be produced causing liner damage and buckling.

3. **What methodologies are available to ensure acceptable COPV performance?**

   a. Burst testing: Currently a 2.0 burst test factor validates the design requirements during qualification phase of COPV design development. Once the COPV design is set and validated by burst test, no further burst testing is conducted during the life of the design.

   b. Proof testing: NASA STD 5019 defines proof as a load or pressure in excess of limit load or the MDP by a defined factor applied to a structure or pressurized hardware to verify structural acceptability or to screen flaws. Therefore, each COPV is proof tested as the last step for final acceptance. Currently, the final verification of carbon fiber integrity after proof testing is by visual inspection. When lowering the proof pressure factor by 50% (1.5 to 1.25), what data are we obtaining that /ensures that the product quality has been maintained? For example, is the lower proof test factor screening for the same defects? Can the lower proof factor allow for subtle (unknown) changes in the

manufacturing process that pass proof testing and then affect operation? There seems to be no published consideration of the ramification of lowering the proof test factor.

    c.   <u>NDE for fiber breakage:</u> Currently, there is no qualified NDE method for the detection of fiber breakage other than outer surface visual inspection. This is important, because fiber breakage during autofrettage and proof testing is only noted by outer surface visual inspection.

    d.   <u>NDE for metallic liner damage:</u> NDE methods are available to detect liner damage after proof/autofrettage. Laser profilometry measurements have been demonstrated for detection of liner deformation (buckling) after autofrettage. Upon completion of a probability-of-detection (POD) study, an eddy current method will be available for use for the detection of liner cracking after proof testing.

4. **What alternate approaches have been suggested to mitigate the composite damage concern resulting from fiber breakage?** No alternative strategies have been noted during this rapid review to mitigate fiber breakage. If the current fiber-breakage model is used to rationalize a proof test factor/autofrettage pressure, it could also be used to rationalize added carbon fiber overwrap to low fiber strain to an acceptable level. Obviously, added carbon fiber overwrap will result in increased weight. The results of a valid trade were not found that weighs the risks/costs of lower proof versus alternatives.

Summary

This review suggests the lowering of the COPV proof factor is based on:

1. Use of a fiber breakage model that is not validated by test and was characterized as having significant shortcomings.

2. Lack of historical data as to the successful use of 1.5 proof pressure factor.

3. Lack of justification as to how the lower proof test factor affects verification of structural acceptability or to screen for flaws.

4. Lack of any trade studies as to other alternate approaches to mitigate autofrettage effects.

5. Substantial number of non-conformances related to structure and fracture control proof factor requirements with a lack of available technical rationale have been identified.

It is highly recommended that a thorough independent assessment be conducted to understand COPV state-of-the-art as it relates to proof test and autofrettage requirements.

ATTACHMENT #1

NASA-STD-5019 Fracture Control Requirements for Spaceflight Hardware

1.2 Purpose

Fracture control is implemented to reduce the risk of a catastrophic failure from a defect or damage. The intent of this standard is to provide fracture control requirements for spaceflight hardware. A variety of fracture control considerations and options are addressed, some of which may not be applicable to a given design. Information is provided to assist the user in the development of an effective Fracture Control Plan and other fracture control documentation.

4.1.2.1.3 COPVs

COPVs shall comply with the latest revision of ANSI/AIAA Standard S-081, Space Systems-Composite Overwrapped Pressure Vessels (COPVs), with the following tailoring:

a. MDP* shall be substituted for all references to MEOP (Maximum Expected Operating Pressure).

b. Mechanical damage control shall include protective covers and damage indicators as a minimum unless otherwise approved by the RFCB [Responsible Fracture Control Board].

c. If damage indicators are utilized, the indicator shall be inspected between missions.

*Maximum Design Pressure (MDP): For a pressurized system, the highest pressure defined by the maximum relief pressure, maximum regulator pressure, maximum temperature, and transient pressure excursions based on two credible system failures.

4.2.4.4 Flaw Screening for Fracture-Critical Parts

a. Fracture-critical parts shall be screened for flaws by NDE, proof testing, or process control.

b. RFCB approval shall be required for flaw screening by proof tests or process control.

4.2.4.4.1 NDE

a. NDE shall be done on fracture-critical parts to establish that a low probability of preexisting flaws is present in the hardware.

b. NDE inspections for fracture control shall be performed in accordance with NASA STD-(I)-5009 for metallic components and meet the intent of MIL-HDBK-6870 for composite components.

c. Hardware that is proof tested as part of its acceptance (i.e., not screening for specific flaws) shall receive post-proof NDE at critical welds and other critical locations identified in the

Fracture Control Plan.

4.2.4.4.2 Proof Test*

a. Prior approval shall be required from the RFCB when a proof test is used as the flaw screening technique.

b. Documented rationale shall be provided, demonstrating the component is not expected to experience significant crack growth during the proof test, and/or a presumed crack size after the proof test adequately accounts for growth during the test and demonstrates adequate damage tolerant life.

c. When it is judged that a proof test is appropriate to screen a component or structure for flaws, the proof test shall occur at the in-service temperature and environment.

* Proof Test: A load or pressure in excess of limit load or the MDP by a defined factor applied to a structure or pressurized hardware to verify structural acceptability or to screen flaws.

4.2.4.4.3 Process Control

a. Prior approval shall be required from the RFCB (Responsible Fracture Control Board) when process control is used to determine the initial defect sizes for damage tolerant analysis and/or testing.

b. Process control rationale submitted for RFCB approval shall include a statement explaining why this alternate approach is being applied, an overview of the hardware, the manufacturer's experience base, process control during manufacture and subsequent life of the component, all component testing, and summary arguments.

ATTACHMENT #2

ANSI/AIAA S-081-2000 Space Systems – Composite Overwrapped Pressure Vessels (COPV)

5.1 Acceptance Test Requirements

Acceptance tests shall be conducted on every COPV to verify workmanship and identify manufacturing defects. Accept/reject criteria shall be formulated prior to tests. The test fixtures and support structures shall be designed to permit application of all test loads without jeopardizing the flightworthiness of the test article. As a minimum, the following tests are required:

(a) General inspection per Section 4.5.1,

(b) Proof pressure testing,

(c) Leak testing.

5.1.1 Non-Destructive Inspection

Every COPV shall be subjected to visual and other non-destructive inspection (NDI), per the inspection plan of Section 4.5.1, to establish the initial and post-proof condition of the fabricated vessel. The inspection shall include a volumetric and surface inspection by the selected NDI techniques.

The selected NDI techniques and inspection sensitivity for the metallic liner shall be according to Section 4.5.2 when safe-life demonstration is required.

The NDI techniques selected for inspecting the composite overwrap of pressure vessels shall be according to Section 4.5.2.

5.1.2 Proof Testing

The COPV shall be proof tested to a minimum pressure of:

P = (1 + Burst Factor)/2 X MEOP (for a burst factor less than 2.0) or

=1.5 X MEOP for a burst factor equal to or greater than 2.0

where MEOP is the Maximum Expected Operating Pressure. Unless otherwise stated, the duration of the proof test shall be sufficient to verify pressure stability. The COPV shall not leak, rupture, or experience detrimental deformation during proof testing. Proof-test fluids shall be compatible with the structural materials used in the COPV and not pose a hazard to test personnel. The proof test fixture shall emulate the structural response or reaction loads of the flight mounting where COPV mounting induces axial or radial restrictions on the pressure driven expansion of the vessel. The temperature shall be consistent with the critical use temperature, or test pressures shall be suitably adjusted to account for worst-case temperature effects on static strength and/or fracture toughness

5.1.3 Leak Testing

The COPV shall be leak tested at MEOP or greater.

5.2 Qualification Testing

Qualification tests shall be conducted to demonstrate that all design requirements are met. The qualification test procedure shall be approved by the procurement agency prior to the start of qualification testing.

As a minimum, the following tests shall be conducted on all new or substantially modified COPV designs:

Safe-life demonstration per Section 5.2.1, or LBB [leak-before-burst] demonstration according to Section 5.2.2.

(a) Acceptance test per Section 5.1

(b) Pressure cycle testing per Section 5.2.3

(c) Vibration/External load testing according to Section 5.2.4

(d) Leak testing according to Section 5.1.3

(e) Burst testing according to Section 5.2.5

Qualification testing of COPVs that are similar to previously qualified vessels may be reduced subject to the approval of the procurement agency and appropriate range safety authority.

If required, damage tolerance testing shall be conducted according to Section 4.2.10.3. The test article(s) may be the same as the ones used previously or may be separate as defined in the test plan.

When conducting qualification testing, the test fixtures support structures, and methods of environmental application shall not induce erroneous or unrealistic test conditions for the intended application. The types of instrumentation for measuring stresses and displacements and their locations in qualification tests shall be based on the results of the stress analysis (Section 4.2.5). Additional instrumentation shall be installed to provide complete monitoring and control of the test fixtures and hardware including temperature, pressure, and other critical parameters. The instrumentation and test plan shall be formulated to provide sufficient data to ensure proper application of input loads, pressures, environments, and vessel responses to allow assessment against accept/reject criteria, which shall be established prior to test. The sequences, combinations, levels, and duration of loads, pressure, and environments shall demonstrate that design requirements have been met.

5.2.5 Burst Test

Burst testing shall be conducted to verify compliance to the burst factor requirement defined in Section 4.2.2 in compliance with the verification requirements of Table 1.

The design burst should be maintained for a period of time sufficient to assure that the proper pressure is achieved. The vessel shall not burst prior to the end of this period of time. After demonstrating the burst pressure, the pressure shall be increased at a controlled rate until vessel burst occurs.

The burst test fixture shall simulate the structural response or reaction loads of the flight mounting where COPV mounting induces axial or radial restrictions on the pressure driven expansion of the vessel.

ATTACHMENT #3

JSC 65828 Rev. A – Structural Design Requirements and Factors on Safety for Spaceflight Hardware

3.3   PURPOSE

This document establishes the structural requirements for human-rated spaceflight hardware including launch vehicles, spacecraft and payloads. These requirements are applicable to Government Furnished Equipment activities as well as all related contractor, subcontractor and commercial efforts. These requirements are not imposed on systems other than human-rated spacecraft, such as ground test articles, but may be tailored for use in specific cases where it is prudent to do so such as for personnel safety or when assets are at risk.

The requirements in this document are focused on design rather than verification. Implementation of the requirements is expected to be described in a Structural Verification Plan (SVP), which should describe the verification of each structural item for the applicable requirements. The SVP may also document unique verifications that meet or exceed these requirements with NASA Technical Authority approval.

3.2.8.5 Composite Overwrapped Pressure Vessels

[STR0023] Composite Overwrapped Pressure Vessels (COPVs) shall comply with ANSI/AIAA-S-081, Standard for Space Systems – Composite Overwrapped Pressure Vessels (COPVs), with the following exceptions:

a. Applicable loads and environments to be used in place of those derived following the AIAA standard are defined in JSC 65829, Loads and Structural Dynamics Requirements for Spaceflight Hardware.

b. Applicable minimum factors of safety to be used in place of those defined in the AIAA standard are defined in Section 3.3.1.6.

c. Applicable design pressures to be used in place of those defined in the AIAA standard are defined in Section 3.2.8.2.

Rationale: The AIAA standard for COPVs is tailored to account for human spaceflight safety factor requirements and design loads.

3.3.1.6 Pressurized Hardware

[STR0044] Pressurized hardware shall be designed and tested to the minimum factors of safety specified in Table 3.3.1.6-1.

Rationale: Proof tests are conducted as an acceptance test of each production unit including the qualification article. The proof factor is the minimum required. A higher proof test factor may be determined by fracture mechanics analysis when the proof test is used for flaw screening.

Additional factor of safety requirements for liquid propulsion engine structures and solid rocket motors are provided in Sections 3.3.1.7 and 3.3.1.8, respectively.
MDP = Maximum Design Pressure
MEP = Maximum External Pressure
[STR0045]

Table 3.3.1.6-1 – Minimum Factors of Safety for Pressurized Hardware

Composite Overwrapped Pressure Vessels (COPV)

Proof Pressure	1.25 x MDP
Design Burst Pressure	2.00 x MDP
Negative Pressure Differential*	1.00 x MEP

*Must be capable of withstanding maximum external pressure multiplied by ultimate factor of safety (Negative Pressure Differential) without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

Appendix D: 2012 White Paper on the Need for Advanced Engineering Methods

Development of Computational Materials-Based Methods for the Design of Components Having Small Length Scale Features

E.H. Glaessgen
Assistant Branch Head
Durability, Damage Tolerance and Reliability Branch
NASA Langley Research Center

R.S. Piascik
NASA Technical Fellow for Materials
NASA Engineering and Safety Center

Materials Discipline Technology Gap:

Standard engineering fracture and fatigue-based design methods are not applicable for an ever-increasing number of advanced design concepts.

Background:

Many of the advanced design concepts are becoming increasingly aggressive; requiring thinner/smaller features that are subjected to more demanding operating environments. Simultaneously, the requirements for their durability and reliability have increased.

The issue is that NASA is now designing and building components that contain various features that are so small that local material behavior cannot be accurately predicted using standard methods. Typically, these *component* features have length scales that are of similar dimensions to those of the material's *microstructural* features. Examples of newly designed critical components where standard methods are no longer applicable include:

1. Radioisotope thermoelectric generators (RTGs) where the life-limiting component incorporates an extremely thin wall (300 microns or 0.012 inch); here, the thin wall was needed to meet heat transfer requirements.

2. High pressure overwrapped pressure vessels (COPVs) where new concepts require liner wall thickness of 250 microns (0.010 inch); here, the thin liner wall is needed to meet weight requirements and is the life-limiting component.

3. Microelectromechanical systems (MEMS) and micromachines where sub-components having dimensions of only a few microns may fail due to mechanical and/or thermal stresses; here, nanomechanics may be required to capture material response.

4. Thermal barrier coatings where coatings are often only a few hundred microns (~0.010 inch) thick; here, delamination and spallation are life-limiting failure modes.

The absence of a life prediction method to address examples 1 and 2 has recently introduced a true risk where engineers have used inappropriate methods (linear elastic fracture mechanics, LEFM) to determine design life. LEFM is not an appropriate method for these length scales;

LEFM is based on continuum theory and breaks-down at small length scales where microstructural features become important. The use of LEFM will result in inaccurate predictions that may be unconservative and may unknowingly affect safety and mission success. Hence, it is becoming increasingly apparent that there is a growing technology gap where the material modeling capabilities of standard engineering practice are inadequate for a growing number of new designs. Currently, the only approach to offset these deficiencies is to conduct expensive and time-consuming component and full-scale testing of flight hardware. However, this philosophy is counter to the Agency's direction to limit costly testing.

Materials Technical Challenge - Develop Computational Materials-Based Methods for the Design of Components with Service Lives that cannot be Predicted by Standard Methods:

The proposed effort will develop needed physics-based computational and experimental micromechanics methods that will become the basis for a new methodology that is required for design of components having extremely small features. Although these micromechanics methods have traditionally been limited to the research community, recent developments have enabled several of the methods to attain a level of maturity where they are becoming viable for application to address NASA requirements.[1]

Unlike Traditional engineering methods that consider a material to be a continuous and homogenous body (a continuum), micromechanics methods interrogate materials response at a much more fundamental level. As a result, deformation and fracture can be investigated at the scale where the microstructrure (individual grains or crystals in a metal or fibers in a composite) are considered. Hence, micromechanics methods are more appropriate for predicting material failure at small length scales than their continuum analogues and are the basis for powerful predictive tools. Additionally, novel experimental methods are being developed to measure material responses at these small length scales and validate the computational models. When successfully applied to the RTG and COPV components mentioned previously, the micromechanics-based approach will enable development of the rigorous design tool(s) required for these special small-length-scale design applications.

Far Reaching Impact of Computational Materials-Based Predictive Methods:

The proposed development of physics-based micromechanics life prediction is based on a growing National thrust toward a broad materials sub-discipline termed Integrated Computational Materials Engineering, ICME or *computational materials*.[2,3] The computational materials vision is far reaching; computational materials-based methods will be the foundation for responding to future Agency needs from the materials discipline. Computational materials methods will lead to revolutionary rapid materials design and development, desktop materials properties characterization, physics-based life prediction methods, etc. A computational materials vision for the Agency will become a critical materials discipline tool for accelerating the introduction of new materials and for the physics-based prediction of material behavior that will lead to an unprecedented design capability for highly reliable deep space systems.

Schedule, Budget and Other Resources:

The proposed effort will develop micromechanics-based methods for use in certification of thin ($t<0.5$ mm) metallic structures such as RTG and thin COPV liners within the next 5 years. These methods for prediction and characterization of microstructurally small crack initiation and growth will extend recent work by members of the present team.[4,5]

The major components of the work plan include:

1. Identification of a suitable focus problem (e.g., RTG or thin COPV liner)

2. Modification of current micromechanics-based computational and experimental methods to address component-specific requirements

3. Analysis and characterization of the component of interest; validation of analysis

4. Generalization of the methods for a range of similar components

LaRC will develop computational approaches in conjunction with a combined LaRC, GRC [Glenn Research Center], MSFC [Marshall Space Flight Center] and JPL [Jet Propulsion Lab] experimental effort to develop supporting experimental methods. A budget of 8 FTE [Full Time Equivalents] and $850K per year divided among the three participating centers will be required to accomplish this effort. Approximately 15-20 million c.p.u. hours per year on NAS/Pleiades supercomputer will also be required to support the simulations.

References:

1. Glaessgen, E.H., Saether, E., Smith, S.W., Hochhalter, J.D., Yamakov, V.I. and Gupta, V, "Modeling and Characterization of Damage Processes in Metallic Materials," AIAA Paper No. 2011-2177. Proceedings of the 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA, Denver, CO, April 4-7, 2011.

2. Anon., "Materials Genome Initiative for Global Competitiveness," Office of Science and Technology Policy, Washington, D.C., June 2011.

3. Anon., "Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security," National Research Council, Washington, D.C., 2008.

4. Hochhalter, J.D., Littlewood, D.J., Veilleux, M.G., Bozek, J.E., Maniatty, A.M., Rollett, A.D. and Ingraffea, A.R., "A Geometric Approach to Modeling Microstructurally Small Fatigue Crack Formation: III. Development of a Semi-Empirical Model for Nucleation," Modelling and Simulation in Materials Science and Engineering, Vol. 19, No. 3, April 2011.

5. Gupta, V.K. and Agnew, S.R., "Diffraction Characterization of Microstructure Scale Fatigue Crack Growth in a Modern Al-Zn-Mg-Cu Alloy," International Journal of Fatigue, Vol. 42, pp. 131-146, September 2012.

Peer Review Comments:

This white paper was peer reviewed by:

1. The NESC Materials Technical Discipline Team consisting of thirty senior subject matter experts (engineers and scientists) from 8 NASA Centers, academia, industry and DoD.

2. The M&P [Materials and Processes] Steering committee members consisting [of] materials discipline management from all NASA centers.

All review comments were positive. Examples of review comments follow:

Marshall M&P recommends pursuing the development of computational materials-based methods for the design of components small length scale features. We believe the proposed approach could be very useful to many problems, but also recognize that the accomplishment of the stated objectives may not be as near term or as simple as stated in the white paper. Any way we can support the effort, we will be glad to do so.

Wendell R. Colberg

Director: Materials and Processes Laboratory

Marshall Space Flight Center

JPL supports the NESC task entitled: **Development of Computational Materials-Based Methods for the Design of Components Having Small Length Scale Features.**

We agree with using focused needs, i.e. "newly designed critical components," to drive the process of micromechanical computation assessment. We would also encourage 2-3 very small contracts with world-class US faculty to independently assess the plans for these efforts a) an early approach review and b) mid-course to provide guidance/critique. Just for reference I have attached an earlier publication out of Caltech by Michael Ortiz (member of the Computational Solid Mechanics Group).

Tim O'Donnell

Jet Propulsion Laboratory

California Institute of Technology

Manager, Propulsion, Thermal and Materials Engineering

Appendix E: 2016 White Paper on V&V and Predictions

Thoughts on Verification, Validation, Blind Predictions, and Pre-Test Prediction
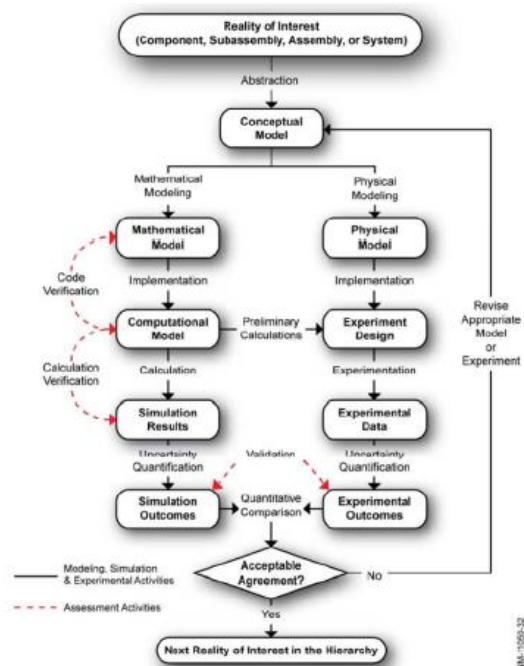
Norm Knight

Scitor, an SAIC Company

Revised July 25, 2016

In some sense, there is confusion related to the words used and likely semantics issues that arise when a verification and validation (V&V) process is advocated. The V&V process increases confidence in the model's predictive capability through quantifying uncertainties and errors by comparing results from the computational model to other analytical solutions and to experimental measurements. The ASME standard processes for V&V activities and products is shown in figure on the right.

Here, some of the V&V terminology will be restated relative to developing a predictive capability for progressive damage analysis of composite structures. Within the V&V framework, one of the challenges is defining appropriate tests (or experiments) to validate an analysis model. A **model** consists of the conceptual, mathematical, and computational (numerical) representations of the physical phenomena needed to represent specific real-world conditions and scenarios. Thus,

From ASME V&V-10-2006 *Guide for Verification and Validation in Computational Solid Mechanics*

the model includes the geometrical representation of the domain, governing equations, boundary and initial conditions, loadings, constitutive models and related material parameters, spatial and temporal approximations (discretization), and numerical solution algorithms (implicit, explicit). This model should imitate or simulate the characteristics of the phenomena using a computational model. The **computational model**, usually in the form of numerical discretization, selected solution algorithm, and defined convergence criteria, is the numerical implementation of the mathematical model. The **mathematical model** involves the mathematical equations, boundary conditions, initial conditions, and modeling data needed to describe the conceptual model. The **conceptual model** is the collection of assumptions and descriptions of physical processes representing the solid mechanics behavior of the reality of interest (i.e., the physical system and its environment) from which the mathematical model and validation tests or experiments can be constructed using the computational model. **Model validation** is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (i.e., the experiment or test). This degree is assessed by one or more **validation metrics** using a

mathematical measure that quantifies the level of agreement between simulation outcomes and experimental/test outcomes.

Validation tests generate data for the purpose of model validation and are defined and developed through cooperative and collaborative efforts between the test engineer and the analyst – usually they are different individuals. A series of such validation tests may be performed as the design progresses through a building-block development process (i.e., replica tests, and/or specific feature tests). Through the V&V, a model can be declared "validated for its intended use" once it has met the **validation requirements**. These requirements are established in the V&V plan and often include descriptions of specific tests that need to be run or other referents (i.e., data, theory or information) that need to be gathered, what specific measurements need to be acquired from the tests, as well as accuracy statements about the agreement between simulation outcomes and experimental/test outcomes.

In my mind, each of the validation tests are guided by pre-test calculations. **Pre-test calculations** are those calculations or simulations performed using a computational model to help design a validation test and may include guidance in how the test should be run, what data should be collected, boundary conditions, pre-test configuration dimensions, generalized imperfections, load introduction, instrumentation layout, etc. In addition to pre-test calculations, pre-test measurements of the test articles and testing environment are also needed as an integral part of the process. Dimensional checks and variability, surface conditions (flat, smooth, imperfect), load introduction process, boundary restraints, and so forth aid in making the test and analysis answer the same question(s).

A concern may [arise] when only one or two tests are performed resulting in the lack of a statistically relevant sample size due to cost or schedule or limited material or a combination of things resulting in an incomplete characterization of all uncertainties in the model or the test. Answers to questions like "what do I change to match the test?" or "which test do I match?" or "what physics was missed?" or "is the response output sensitive to input parameter variations?" or "is the model predictive of the next test?" The goal may then degenerate to putting "dots on the curve" based on a deterministic approach of analyzing each individual test article and comparing the test response of that test article to the analysis result for that test article. Such a pre-test prediction approach only demonstrates that features of interest extracted from the simulation can be matched or correlated to test (i.e., putting "dots on the curve"). However, a *predictive capability* is not demonstrated, in my opinion, because the mechanics of the response may be misinterpreted or overshadowing by sensitivities in the model, variability in the test article, and uncertainties in the test data. That is, the uncertainties associated with this phenomenon and its modeling are either not well understood, not well represented, or both. A blind prediction approach is needed.
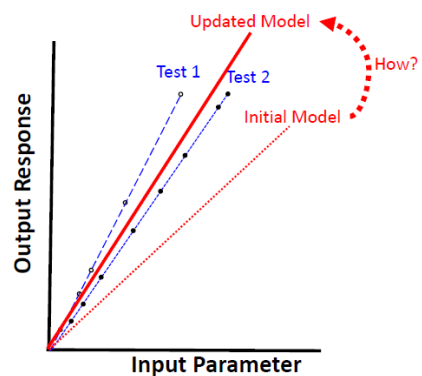
Blind predictions (analyses accounting for uncertainties) **and pre-test prediction** (test article specific analysis) are those predictions from the computational model that are performed and reported without knowledge of or access to the actual test data (i.e., data from strain gages, displacement transducers, digital image correlation, etc.). Within the V&V framework and

documents, a **prediction** is the use of a model to foretell the state of a physical system under conditions for which the model has not been validated. The output from a model that calculates the response of a physical system before experimental data are available to the user. The analyst and the test engineer should be actively engaged in collaborative planning of both the analysis and test to ensure that both efforts are answering the same question and calculating or gathering the same data of interest. In some sense, the test and the analysis are both blind and pre-test calculations may help answer some questions for both testing and analysis. Experienced test engineers and seasoned analysts play crucial roles in this process. A validation test is more concerned that both the analysis and the test answer the same question rather than what the question is. The analysis team should be permitted to witness a test as long as no access to the test data is permitted. An analyst always learns from observing the tests that they are trying to simulate or mimic with an analysis model. Often it was an "I forgot…" that needed an answer. At other times, it helps understand the physical problem and the potential outcome or consequence of the how the analysis may be used.

A prerequisite for access to the test data is the delivery of the blind predictions and/or a pre-test prediction. Usually these simulations are done prior to performing the test in an attempt to mimic the test. Again, a blind prediction that accounts for uncertainties is distinguished from a pre-test prediction that that attempts to mimic a particular test of a specific test article. Scheduling the completion of blind predictions or pre-test prediction should proceed the test but often times this sequencing may not be possible without impacting the testing schedule or the availability of key personnel. Test and analysis schedules should be independent. Some organizations or projects may mandate that testing does not begin until the blind predictions or pre-test prediction are delivered. However, the analysis team could be firewalled off from having access to the actual test data, discussions of observations from testing that would influence the modeling, and any post-test examination results (e.g., X-ray images, photographs, etc.) until the analysis results are delivered. Most likely, some aspects or phases of the testing will be simulated accurately, while other aspects may not due to missing physics, unknown unknowns, or just scatter in the data.

Again, a blind prediction from a V&V perspective is more than a single response curve and more than just a single analysis of the specific test article (i.e., more than a pre-test prediction). Typically, various tolerances, probably not their statistical distributions, are known for the test article configuration. For example, dimensions ± tolerance, thickness ± tolerance, material properties (vendor values vs. independent verification), stiffener spacing and orientation on the panel, stacking sequence variations, thickness variations, generalized imperfections, etc. Blind predictions can be used to identify those features as modeling and analysis parameters (random variables) that may influence the structural response and assess response sensitivities. The number of suspected

random variables (known unknowns) may be reduced based on the blind predictions (i.e., selection/evaluation/elimination of random variables) or even the verification process. A family of response curves (an ensemble of models) are then generated for example using the bounds of the random variables (modeling parameters) as well as using their nominal values. This process also requires the definition of metrics to be used to assess predictive capability. These metrics may include a physical response (e.g., pre-buckling stiffness, buckling load, peak
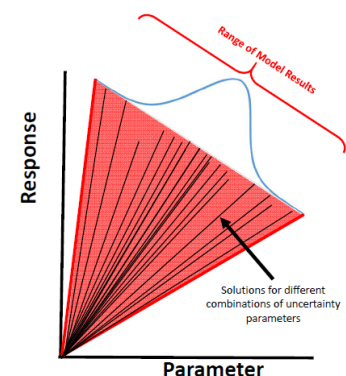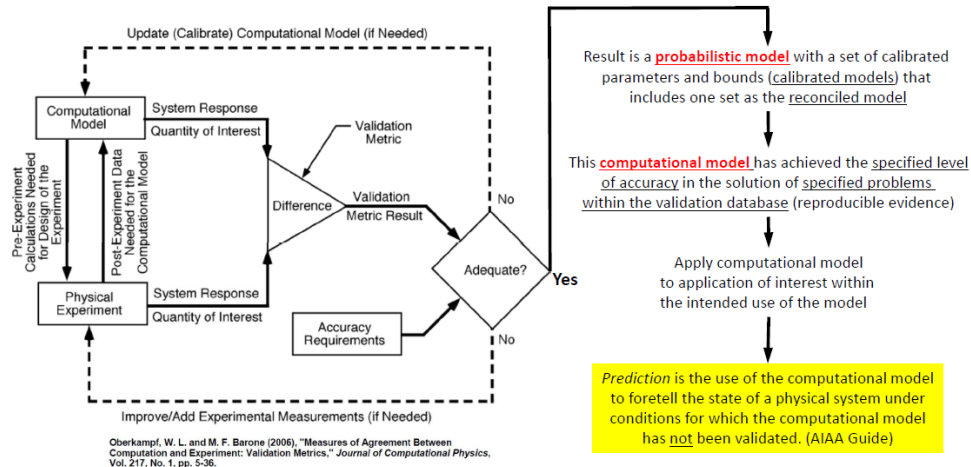
load, load at damage initiation in a particular mode, final failure load, etc.) or a statistical measure (e.g., cumulative distribution function). Understanding what those metrics are and what they represent is a key decision point that needs to be agreed upon jointly by the test engineer and the analyst and likely communicated to the decision makers. For example, does "failure load" mean first material failure, first load drop, loss of numerical convergence, or maybe some time limit? In addition, criteria for success need to be defined either in terms of the response metrics or a percentage of a single metric. The definition of these metrics and success criteria is crucial in evaluating the model's performance and predictive capability as well as the validity of the test data.

As a result, the blind predictions generate a family of response curves (called a "cone" here, others refer to them a "cloud" of results) that ideally bound all test data – this is what would be called a "calibrated" probabilistic model. This **calibrated probabilistic model** includes a combination of modeling and analysis parameters (random variables), their actual or assumed statistical distributions, and the ranges of those parameters. The bounds of the probabilistic model then encompass the bounds of the test data. The analyst should be able to identify within this probabilistic model a single set of random variable values such that the associated analysis result agrees with the mean of the test data – this has been called a "reconciled" model. The goal would be for the mean of the test results, for a given response metric(s), to agree with the analysis result using the reconciled model, which is a single instance of the calibrated probabilistic model. Then, a predictive capability has been demonstrated using a probabilistic model for a specific intended use of the model and given set of assumptions. In reality, the effort depends to some extent on the project schedule, budget, personnel, and experience as we attempt to quantify uncertainties and understand confidence levels that need to be communicated to the decision makers for risk assessment.
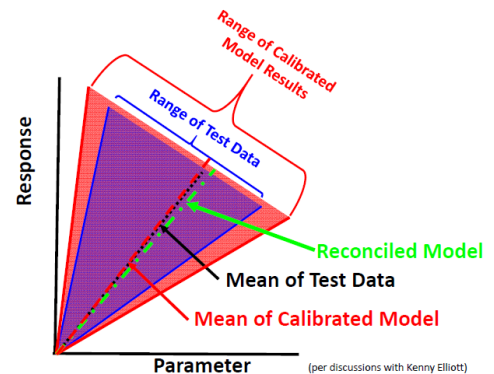
If only one test has been performed, establishing, or claiming to have established, a predictive capability is not realistic, but a blind prediction process (i.e., developing a calibrated probabilistic model) would still be useful. If the test result falls outside the "cone," then obviously the model missed something and a post-test effort is needed. The process of adjusting numerical or physical modeling parameters in the computational model for the purpose of improving agreement with experimental data is often called model update or calibration. Often times, unknown unknowns emerge and cause problems (e.g., premature failure during a test, lack of convergence in analysis); however, they may also identify new aspects of the response that had not been anticipated or may not have been observed previously. Consequently, the analysis and test response should correlate with each other for some portions of the response domain (e.g., initial stiffness, knee in response curve), but may deviate in other regions due to changes in response, damage initiation and progression, changes in damage modes, etc. and thereby require re-visiting the model, the test, the random variables, and/or the metrics to determine the adequacy of the agreement and what it does and does not imply.

Oberkampf, W. L. and M. F. Barone (2006), "Measures of Agreement Between Computation and Experiment: Validation Metrics," *Journal of Computational Physics*, Vol. 217, No. 1, pp. 5-36.

Often times verification steps have been performed previously and the analysis team needs only to adopt the previous modeling strategy for their application or validate a surrogate modeling approach as needed to make the analysis computationally tractable. For example, if the test article has an open hole, then a verification process should have addressed various element issues related to meshing, orientations, recovery of elastic response, sensitivity to element distortion, 2D vs. 3D, single element through thickness vs. fiber-orientated overlaid mesh through the thickness, and so on, as well as issues related to damage initiation and propagation, numerical stability, and convergence.

Another example is related to a stiffened panel test article. Presumably, the response before buckling is elastic with no damage. Are there modeling-related decisions that influence predicting elastic buckling (the eigen pairs)? Does the elastic post-buckling response show any sensitivity to modeling or analysis parameters such as type of imperfections, sign of the imperfections, solver parameters, or solver (implicit vs. explicit)? The analyst would want to understand any modeling/analysis sensitivities affecting an elastic prediction before doing a damage prediction. V&V to meet elastic response metrics provide a validated model for that intended use. Application of those same computational models to simulate damage initiation and progression would constitute a prediction (i.e., use of a validated model beyond its intended use), which may necessitate separate model validation steps.

In summary, blind predictions from a V&V perspective add value and insight to the analysis effort. Test engineers and analysts need to work together and observe each other's process, ask questions, and share thoughts in the development of validation tests through pre-test calculations. Access to test data by the analysis team is restricted until the blind predictions or pre-test prediction are completed and delivered. In my opinion, blind predictions are needed at each level of the building block so that various modeling strategies and model fidelity can be assessed and communicated to the next level. Each level of a testing building block has associated with it an independent modeling and analysis building block leading to credible predictions within each level. If model or tool cannot predict the response of a plate with a hole, what evidence will be needed to show that the response from a more complex structure analysis are credible? Each test has the potential to expose new unknown unknowns. Each analysis has the potential to expose modeling shortcomings or computational limits. Both exhibit uncertainties and limitations. Perhaps the more difficult task is establishing a working dialog and a realization that Murphy's Law is still valid.

Acknowledgements

References

1. Anonymous, *NASA Standard for Models and Simulations*, NASA-STD-7009, National Aeronautics and Space Administration, Washington, D.C., July 2009.

2. Anonymous, AIAA, *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*, American Institute of Aeronautics and Astronautics, AIAA-G-077-1998, Reston, VA, 1998.

3. Anonymous, ASME, *Guide for the Verification and Validation of Computational Solid Mechanics*, American Society of Mechanical Engineers, ASME-V&V-10-2006, New York, 2006.

4. Thacker, B. H., "The Role of Nondeterminism in Verification and Validation of Computational Solid Mechanics Models", Society of Automotive Engineers, SAE Paper 2003-01-1353, 2003.

5. Thacker, B. H., Anderson, M. C., Senseny, P. E., Rodriguez, E. A., "The Role of Nondeterminism in Computational Model Verification and Validation," *Int. J. Materials and Product Technology*, Vol. 25, 2006, pp 144-163.

6. Thacker, B. H., Doebling, S. W., Hemez, F. M., Anderson, M. C., Pepin, J. E., and Rodriguez, E. A., *Concepts of Model Verification and Validation*, Los Alamos Report No. LA-14167-MS, October 2004

7. Roache, P. J., *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albuquerque, NM, 1998.

8. Oberkampf, W. L., Truncano, T. G., and Hirsch, C., *Verification, Validation, and Predictive Capability in Computational Engineering and Physics*, Sandia National Laboratories, SAND Report SAND2003-3769, February 2003.

9. Szabó, B. and Babuška, I., *Introduction to Finite Element Analysis: Formulation, Verification, and Validation*, John Wiley & Sons, 2011.

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE		3. DATES COVERED *(From - To)*
06/02/2017	Technical Memorandum		

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Re-Tooling the Agency's Engineering Predictive Practices for Durability and Damage Tolerance	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Piascik, Robert S.; Knight, Norman F., Jr.	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
	869021.03.07.01.11

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
NASA Langley Research Center Hampton, VA 23681-2199	L-20831 NESC-NPP-17-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	NASA/TM-2017-219621

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 16-Space Transportation and Safety
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Over the past decade, the Agency has placed less emphasis on testing and has increasingly relied on computational methods to assess durability and damage tolerance (D&DT) behavior when evaluating design margins for fracture-critical components. With increased emphasis on computational D&DT methods as the standard practice, it is paramount that capabilities of these methods are understood, the methods are used within their technical limits, and validation by well-designed tests confirms understanding. The D&DT performance of a component is highly dependent on parameters in the neighborhood of the damage. This report discusses D&DT method vulnerabilities.

15. SUBJECT TERMS

Durability and Damage Tolerance; Computational Methods; Finite Element Analysis; NASA Engineering and Safety Center

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	60	(443) 757-5802