Aviation Safety Program

Aircraft Aging & Durability Project

Technical Plan Summary

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This document was developed over the past several months by NASA to define the rationale, scope and detailed content of a comprehensive Aviation Safety, Aircraft Aging and Durability research project. It contains reference to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The document also references potential opportunities for cooperation with external organizations in areas that are currently considered to be of common interest or benefit to NASA. This document should be considered a reference document and not a completed research plan.

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Acronym List

AAD	Aircraft Aging & Durability
AADP	Aircraft Aging & Durability Project
ADP	Advanced Digital Processing
AvSP	Aviation Safety Program
CDM	Continuum Damage Mechanics
CP	Challenge Problem
CTOA	Crack Tip Opening Angle
DoD	Department of Defense
EBSD	Electron Back-scattered Diffraction
ESEM	Environmental Scanning Electron Microscope
FAA	Federal Aviation Administration
FE	Finite Element
IL	Integration Lead
IVHM	Integrated Vehicle Health Management
MD	Molecular Dynamics
NASA	National Aeronautics and Space Administration
NASIP	NASA Aircraft Structural Integrity Program
NDE	NonDestructive Evaluation
NESC	NASA Engineering and Safety Center
NGATS	Next Generation Air Transportation System
NRA	NASA Research Announcement
PMC	Polymeric Matrix Composites
POD	Probability of Detection
RVE	Representative Volume Element
RTF	Return to Flight (Space Shuttle Program)
SAA	Space Act Agreements
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscope
SOA	State-of-the-Art
STAGS	Structural Analysis of General Shells
UT	Ultrasonic
UTAP	UT Phase Array Test-bed
WWFE	World Wide Failure Exercise

Technical Plan

1. Relevance

The Aircraft Aging and Durability Project (AADP) is part of the Aviation Safety Program (AvSP). The AvSP is building upon the unique safety-related research capabilities of NASA to improve aircraft safety for current and future civilian and military aircraft, and to overcome aircraft safety technological barriers that would otherwise constrain the full realization of the Next Generation Air Transportation System (NGATS). The Program will provide long-term investment in research to support and sustain expert competency in critical core areas of aircraft safety.

Aircraft aging is a significant national issue. For economic reasons, commercial airline carriers and the DoD are flying their vehicles longer, often exceeding the original design service life of the vehicles. The average age of the commercial fleet, which reduced after 9/11 as older vehicles were parked, is increasing, particularly in the wide-body class. The DoD is replacing its fleet at less than half the rate required to even maintain the current average age. There is also technology pull for aging-related research for space applications. Both NASA and DoD are confronted with maintaining their aging space assets, and the Exploration Initiative with long endurance flight missions and habitats will have elevated durability requirements.

Previous research in aging has maintained sufficient safety for current vehicles, but with significant labor and economic costs. The cost of aging has a compound nature, as growing sustainment costs reduce the ability to purchase new vehicles. Previous research has been largely reactive in nature, and based more on observations than on fundamental understanding. Emerging civilian and military aircraft (A380, B787, YF-22, JSF) are introducing (in primary structures applications) advanced material systems, fabrication techniques, and structural configurations for which there is very limited service history, and there is concern over the ability to ensure continued airworthiness of these aircraft over their life cycles. The focus of the AADP is on aging and damage processes in 'young' aircraft, rather than life extension of legacy vehicles. There will be an emphasis on new and emerging material systems/fabrication techniques and the potential hazards associated with aging-related degradation. The intent is to take a proactive approach to identify aging-related hazards before they become critical, and to develop technology and processes to incorporate aging mitigation and maintenance into the design of future aircraft.

The goal of the AADP is to perform foundational research in aging science that will ultimately yield multi-disciplinary analysis and optimization capabilities that will enable system-level integrated methods for the detection, prediction and mitigation/management of aging-related hazards for future civilian and military aircraft. The Project is organized relative to these three theme areas:

- Detect – locate and characterize fully damage or degradation of materials and structures.
- Predict – life and strength predictions accounting for accumulated damage associated with long-term exposure to thermal/mechanical/environmental loads
- Mitigate – concepts to prevent, contain, or manage degradation associated with aging

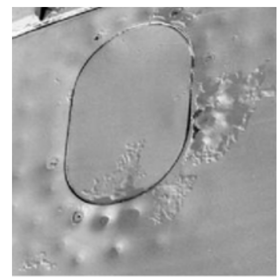
The scope and technical content of the AADP is intended to accomplish two objectives: (1) to deliver specific products to address end-user problems and needs, and (2) to develop fundamental technology (not specific to a single application) to enable integrated multi-disciplinary tools.

1.1 Objective 1: Specific Products to Address End-User Problems and Needs

The first objective was addressed during project planning by establishing a set of Challenge Problems (CP) that describes application-specific physical problems to be addressed by the Project. Challenge Problems were selected based upon a number of factors. NASA experts experienced with Aeronautics and Shuttle Programs, along with representatives from the FAA and DoD, drew upon their experiences and vision for the future, to identify Challenge Problems that met the following criteria: aero-centric, safety critical, aging related, and containing technology development needs aligned with NASA's core capabilities and charter. The eight Challenge Problems selected for the AADP are summarized in Table I. Presented for each CP is a brief description of the problem, the demonstrated need, the AAD Project content, and the value-added contribution of the research. The Challenge Problems provide focus toward the needs of users, and serve as anchor points for the relevance of the project.

Table I. – Project Challenge Problem Summaries

CP-01: Damage Methodology for Metallic Airframe Structures



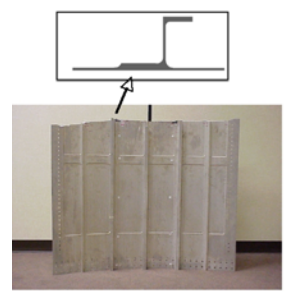
Problem: Conventional life prediction uses fracture mechanics assessments for cycle-based life with estimated initial flaw. Little understanding of crack initiation and small crack growth processes, which is majority of life. Fails to address synergistic time and cycle dependent processes. (AAD to focus on current and emerging alloys rather than legacy materials)

Demonstrated Need: Aging involves complex interaction of load and environmental effects. Current environmental cracking solutions are empirical and of limited use for new material systems

AAD Project Content: NDE techniques for bond strength and corrosion characterization; Physics-based predictive tools for crack propagation; Integrated time and cycle dependent processes; Robust closure models for crack growth evaluation.

Value Added Contribution: Physics-based damage models for development of material design tools

CP-02: Structural Integrity of Integral Metallic Structure



Problem: The use of integral metallic structure in airframe application provide unique crack growth and fracture characteristics that are not consistent with traditional metallic structure. Predictive capabilities for crack path are required for residual strength and crack growth.

Demonstrated Need: Increased use of integral metallic structures to reduce weight and part count. New selectively-reinforced concepts competitive with composite structures

AAD Project Content: NDE for cracks with non-uniform cross section; Predictive capability for crack path deflection; 3D FEM-based models to assess crack growth.

Value Added Contribution: Predictive tools provide improved lifing/inspection protocols. Enable alternatives to composite structures

CP-03: Durability and Structural Integrity of Composite Skin-Stringer Fuselage Structure

787 Composite Fuselage Barrel

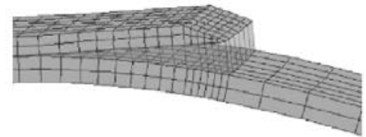
Problem: Increased use of composites and metal/composite hybrids in fuselage structure. Life and safety are based on damage accumulation and environmentally induced changes in material. Failure, degradation, damage accumulation and strength cannot be predicted.

Demonstrated Need: Increased composites and metal/composite hybrids in fuselage structure. Empirically based building-block design and certification approaches are expensive/highly conservative. Design margins not well quantified. Research pull by manufacturers, operators, NASA space programs, FAA

AAD Project Content: ID critical failure and degradation mechanisms; ID critical maintenance and inspection risks; Predictive models for damage initiation/growth and residual strength; Mitigation strategies: material development, structural design, operational procedures.

Value Added Contribution: Reliable strength/life prediction methods accounting for aging degradation. Reduced empiricism in design and certification / reduced design cycle time.

CP-04: Durable Bonded Joints



Problem: Adhesive bonds are critical to integrity of built-up structure. Disbonds (gaps) can often be detected; the strength of the adhesion between surfaces in contact is not obvious. Need to detect bond degradation, predict disbond growth, and prevent weak bonds.

Demonstrated Need: Increased use of bonded joints to reduce part count. FAA: contamination/surface prep is #1 problem in bonded structure. Recent examples of weak or degraded bonds causing structural failure. NTSB: Airbus rudder delamination associated with fluid ingression

AAD Project Content: NDE technology for bond strength; Damage projection procedure for high-cycle fatigue; New adhesives and forgiving processes for construction and repair.

Value Added Contribution: Novel NDI technology for bond strength. Chemistry approaches to improved adhesives/surface treatments. Mechanics predictions for degrading material.

CP-05: Durability of Engine Fan Containment Structure

Engine Blade-off Test

Problem: For advanced composite concepts for jet engine containment structures (not current metallic cases with dry Kevlar overwraps), long-term service/environment effects are unknown. Better models/tools are needed for predicting engine blade-off event physics (high strain-rate impact) to reduce risk and cost.

Demonstrated Need: New lightweight advanced composite concepts are under development (user pull). Fan containment is safety critical.

AAD Project Content: Methods to quantify life cycle performance degradation and safety of composite jet engine containment structures; Models and simulation tools for blade-off events. NDE techniques for quality assurance, damage assessment, and model improvement.

Value Added Contribution: Models of aging and configuration effects for optimal safety and efficiency. Improved 'standardized' tools for blade-out event simulation and new NDE techniques enable acceptance of advanced concepts

CP-06: Durability of Engine Superalloy Disks

Problem: New nickel based superalloys which enable higher disk operating temperatures have been developed. However, long term durability and aging characteristics of these new alloys must be understood and addressed to prevent potential fleet problems.

Demonstrated Need: Disk failures are rare but cannot be contained and are generally catastrophic. Before new disk alloys can be used at higher operating temperatures to improve operating efficiencies, their long term durability must be understood and improved if necessary.

AAD Project Content: Models to predict degradation of new alloys by microstructural instability and corrosion; Mitigation concepts: coatings/surface treatment to reduce corrosion, heat treatment to enhance fatigue durability

Value Added Contribution: Assured durability of new disk alloys at higher operating temperatures. Enables improved engine efficiency while retaining safety

CP-07: Durability of Engine Hot Section

Problem: Degradation and damage that develops over time in hot section components can lead to catastrophic failure. Poor characterization of degradation processes in harsh environment conditions hinders development of durable hot section components

Demonstrated Need: Very difficult to model turbine blade temperatures, strains, heat fluxes; measurements are needed. The turbine section has been consistently responsible for >$40M/yr in losses to the Air Force (second leading cause of aircraft damage)

AAD Project Content: Develop thin film and nano sensors to measure temperature, strain, and heat flux during aging studies for hot propulsion materials.

Value Added Contribution: New bulk and nano-structured sensor materials and novel thin film harsh environment sensors provide high temperature characterization for use in component durability improvement.

CP-08: Wiring Degradation and Faults

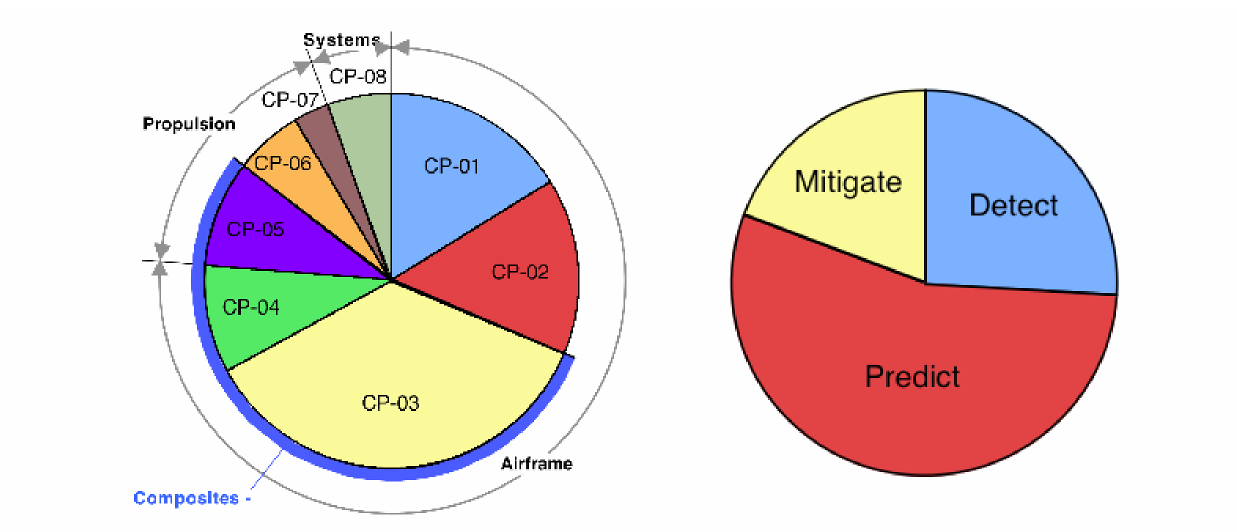
Problem: Faults and hazards in aging vehicle wiring persist as a problem in legacy vehicles, and will pose risks in new vehicles. Electrical failures from shorts, opens, insulation degradation or overloaded circuits can have catastrophic effects.

Demonstrated Need: Electrical failures from shorts, opens, insulation degradation or overloaded circuits can have catastrophic effects in legacy and new vehicles. Attempts to contain damage after system failure don't always work

AAD Project Content: NDE to detect wiring and circuit degradation/defects; predictive software incorporating NDE data; next-generation sensored/fault-tolerant distributed wiring design

Value Added Contribution: Predictive tool for condition-based maintenance reduces risk. Next-generation sensored/fault-tolerant distributed wiring designs

For each Challenge Problem, detailed plans were constructed that included task descriptions, milestones, deliverables and resources. The eight Challenge Problems outlined above represent the breadth of the research portfolio for the AADP. To give an indication of the distribution of Project resources across the research portfolio, the AADP FY07 workforce distribution for the eight Challenge Problems and the three Project Theme areas, (Detect, Predict, and Mitigate) is shown in Figure 1. The pie chart in Figure 1a indicates relative investment across the Challenge Problems. Challenge Problems CP-01 to CP-04 address airframe applications and engage 76% of the workforce. CP-05 to CP-07 address propulsion applications and engage 18% of the workforce, and CP-08 (wiring) is the only Systems application and engages 6% of the FY07 workforce. On the perimeter of the pie chart in Figure 1a, a thick blue ring identifies CP-03 to CP-05 as Challenge Problems addressing



(a) Workforce by Challenge Problem (b) Workforce by Theme

Figure 1. AADP Workforce distribution by Challenge Problem and Theme

composite material applications, indicating that just over half of the Project workforce is working in composites. The pie chart in Figure 1b indicates that the Project workforce is deployed against the Detect, Predict, and Mitigate themes, at about 25%, 55%, and 20%, respectively. As mentioned above, just over half of the Project resources address composite material applications. From a historical perspective, DOD programs such as the Composites Affordability Initiative (CAI) and Advanced Insertion of Materials-Composites (AIM-C) helped reduce implementation costs of Polymeric Matrix Composites (PMCs) while increasing confidence in the use of these materials. Research contributions of the Langley Research Center also played a key role in the widespread acceptance and application of emerging composite technology for both civil and military aircraft. Fundamental advances in composite materials and structures technology made during basic fundamental research programs and focused research programs such as the Aircraft Energy Efficiency (ACEE), the Advanced Composites Technology (ACT), and the Advanced Subsonic Technology (AST) Programs significantly accelerated the use of composite materials for secondary airframe structure by increasing industry's confidence in the safety and economic feasibility of these materials. In the decades since the introduction of polymeric composite materials for use in aerospace applications, their application to primary structure has not been realized because of potential acquisition costs issues and technological barriers that have limited the confidence necessary to proceed with production of high-risk primary structures. One major technological barrier is the inability to predict reliably the structural integrity and life of composite structures under potentially severe operating conditions due to inadequate understanding of the underlying physical mechanisms for material degradation, damage evolution, and failure. These limitations of understanding have caused the design of composites components to be largely empirical and based on relatively crude knock-down factors, or similar approaches, to account for uncertainty in strength prediction and the long term evolution of material properties. Consequently polymeric composite structures are often over-designed, and in some situations polymeric composite structures are not used because the over-designed part does not provide a design advantage. Commercial aircraft currently under development, such as the Boeing 787, are projected to extensively use polymeric composite materials throughout the aircraft, including primary structure. The percentage of structural weight that is composite material in the B777, A380 and B787 aircraft is estimated at 12%, 25%, and 50% respectively. It is in the national interest for NASA to invest in technologies that can impact the reliability and safety of these and similar aircraft and that can have an influence on the design of future aerospace vehicles.

However, metallic materials will most likely comprise a significant fraction of the materials used in airframe structures for many years to come and these materials will be produced in novel configurations. For metallic materials to be competitive with composite materials from a weight perspective, new integral metallic materials and hybrid laminate materials are being developed. Therefore, research to understand damage processes in these product forms and to develop NDE tools to monitor damage must be addressed. Technology advances are making it possible to model damage at a scale that has not been previously possible. Atomistic models of damage propagation can now be applied to engineering materials. Multiscale micromechanical models for metallic and composite materials will be developed in this program. While composite materials pose some unique damage processes that will require unique approaches that are not necessarily valid for metallic materials, it is the intent of this program to continually assess the progress of the modeling efforts for both material systems and to assess how results from one material system may benefit the other. Characterization techniques for interrogating metallic materials and the understanding of damage processes are much more advanced for metallic materials. Consequently, the modeling of damage in metallic materials will provide opportunities to validate the multiscale models being developed that would not be available if this work were to only focus on composite materials. The use of atomistic modeling to assess damage processes is unique to the plan and is not detailed in any other current research plans.

Several of the principles in the NGATS vision for a flexible, resilient, scalable, adaptive and highly automated system will be supported by AAD research. One of the principles, Integrated Environmental Performance, involves addressing environmental issues in a way so as not to hinder growth, nor impede the ability to meet demand. AAD research in lightweight engine fan containment and higher operating temperature turbine disk materials will enable new engine configurations for current and future vehicles that burn less fuel and generate less noise. Another principle, Proactive Approach to Safety Risk Management, speaks to assessing risk and anticipating potential safety problems so we can prevent accidents before they happen. Integrated methods developed by AAD to characterize aging-related degradation, model failure mechanisms and useful life, and mitigate the hazards, will provide data and capabilities to enable condition-based maintenance of vehicles.

The majority of the AADP addresses lifing and integrity of structural components. The one Challenge Problem in an ‘aging systems’ category is CP-08: Wiring Degradation and Faults. The aging of vehicle electrical wiring persists as a problem in legacy vehicles, and will continue to pose risks in new vehicles, even as new materials are introduced. To better understand the effects of aging on emerging electrical systems, it is important to develop tools that can characterize degradation (such as loss of dielectric properties in insulation, or corrosion in connectors) in current electrical wiring systems. Similarly, modeling electrical wiring failure modes and mechanisms, and useful life (especially in insulation materials) can provide predictive capabilities enabling condition-based maintenance of vehicles. These initial development tools can then be expanded to assist in the mitigation of wiring degradation. They can also be used to assess emerging wiring technology for aging characteristics under various operating environments. Development of this technology will assist in enabling goals of NGATS by embedding safety and reliability into next generation aircraft wiring harnesses and systems.

1.2 Objective 2: Fundamental Technology Development

To address the second objective, fundamental technology development not specific to a single application, the AADP has defined a four-level approach to technology development and integration (shown in Figure 2) and will conduct research across each of these levels to address evolving safety challenges.

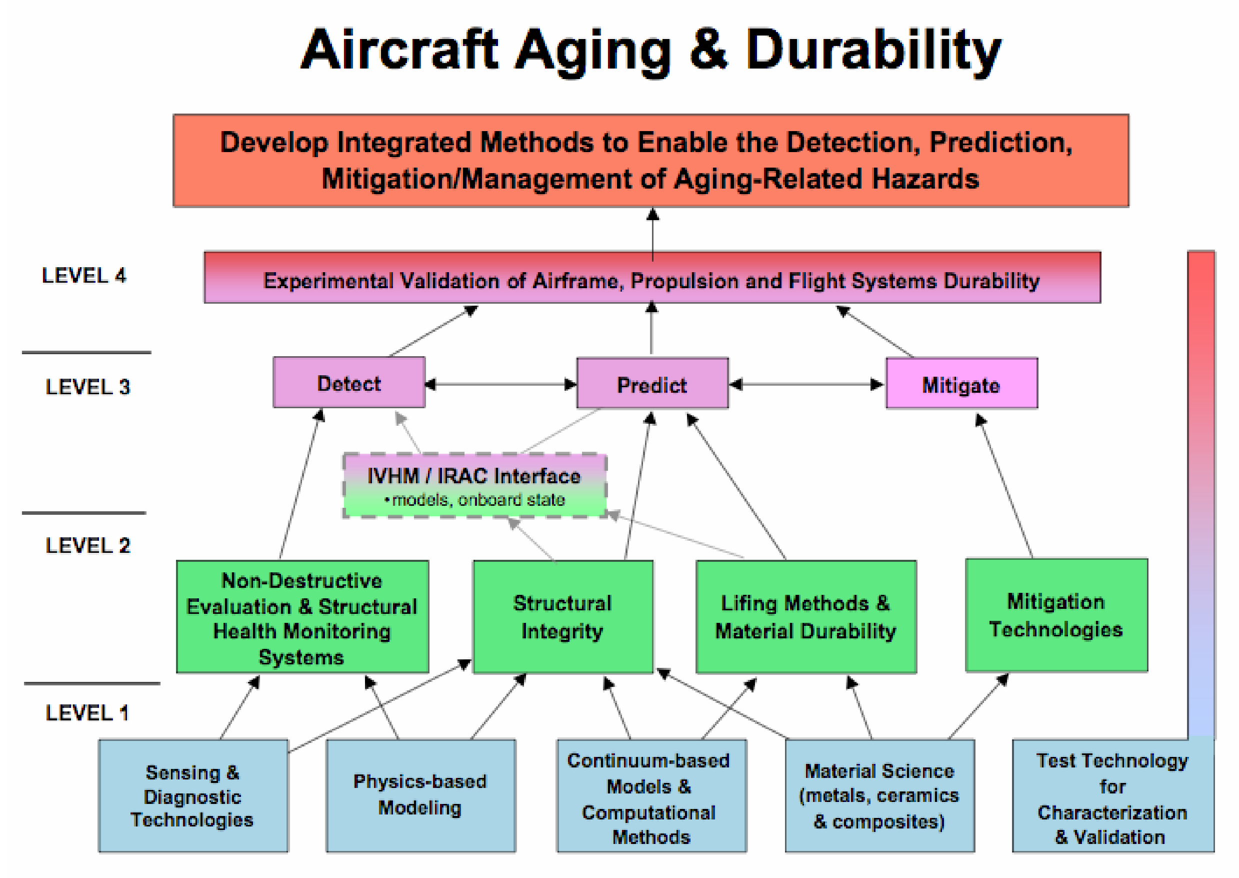


Figure 2. Aircraft Aging and Durability Project Concept.

At Level 1, foundational research will be conducted in sensing and diagnostic technologies; physics-based modeling; continuum-based models and computational methods; material science (metals, ceramics, composites); and characterization/validation test techniques; to further the fundamental understanding of the underlying physics and develop an ability to model that physics. At Level 2, the foundational research is leveraged to develop NDE Systems; Structural Integrity tools; Lifing methods; and Mitigation concepts; producing technologies and analytical tools focused on discipline-based solutions. At Level 3, multi-disciplinary methods and technologies are developed to balance solutions across disciplines. Detect capability is enhanced by coupling NDE and structural integrity analysis, Predict capability is enhanced by applying NDE (and IVHM data) to improve model input and provide improved remaining life and strength predictions, and Mitigate is enhanced by applying predictive models to develop advanced mitigation concepts. At Level 4, results from Levels 1 through 3 activities are built upon to integrate Detect, Predict, and Mitigate capabilities for system-level performance, and system-level experiments are conducted for validation. The development path for the Detect, Predict, and Mitigate themes are highlighted in the figure by color-coded box frames for each theme. The Test Technology element supports each theme and spans all four levels of the diagram.

1.3 Integration of Objectives to Complete the AADP Technical Plan

To construct the AAD Project, a matrix structure was developed by mapping the detailed plans for each CP (Figure 1, for example) onto the theme-based Project concept shown in Figure 2.

The resulting matrix structure for the AAD Technical Plan is shown in Figure 3. The rows of the matrix contain the Project Themes and levels, where the numbers in parentheses correspond to the Level and box number in the four-level Project Concept. The columns in the matrix are populated with the content of each Challenge Problem. The Project is to be managed by theme/discipline, in each row cross-cutting specific applications to deliver integrated fundamental technology. Meanwhile, the Challenge Problems remain intact, with 'Challenge Problem Owners' promoting integration in each column to deliver application –specific products.

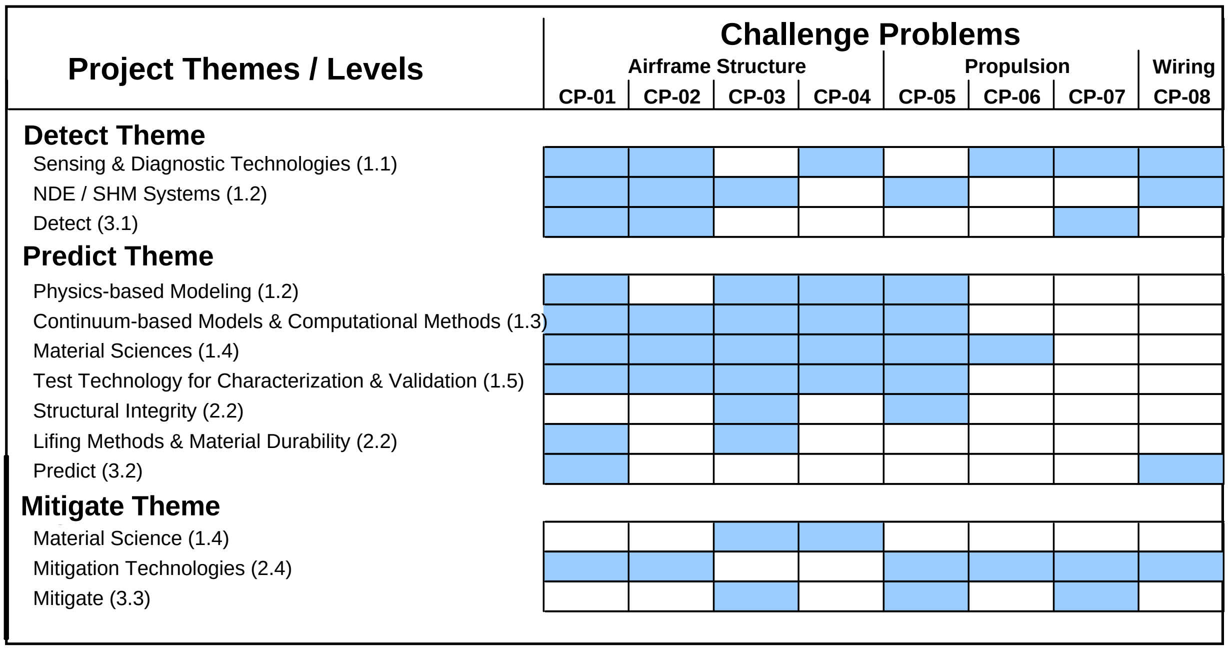


Figure 3. AADP Technical Plan: Matrix structure; Challenge Problems (columns) mapped to theme-based research thrusts from the AAD Project Concept, or 'Box-Chart' (rows)

1.4 Project Content Relative to Other Projects and Programs

The NASA Fundamental Aeronautics Program (FAP) contains numerous elements that complement content within the AADP. Projects within the FAP are focused on the science and application of technology to various vehicle classes, which by necessity includes the need to address basic aging and durability issues in order to successfully meet their goals of developing advanced capability in hypersonic, supersonic, and subsonic flight. To avoid duplication of content between the FAP and AvSP a cross-program integration meeting was held Dec. 9, 2005 in Washington D.C. The outcome from this meeting and the content of the plans from the FAP projects supports the following statements. The primary objective of FAP projects is to develop performance-based technologies for nominal vehicle operation conditions. New vehicle concepts and structural configurations are developed to enhance vehicle performance (noise, drag, fuel efficiency) without sacrificing damage tolerance. Thus, in the FAP, durability and damage tolerance is generally one of the constraints in a vehicle performance optimization process. Conversely, in AADP durability and damage tolerance is the function to be optimized. AADP is responsible for developing damage analysis tools (residual strength, accumulated damage, degradation models, and FAP performs damage tolerant design. There are elements within AADP that initiates development of design technology for aging, with the long–term goal of transferring capability into FAP design tools. Likewise, FAP develops materials for nominal performance characteristics, while AADP performs material development and characterization specific to aging, degradation and damage effects. An example for engine fan containment systems demonstrates the difference focus between AADP and FAP. AADP plans to evaluate the long-term durability of recently developed all-composite cases. FAP explores possibilities for making engine fan cases more "multi-functional", e.g. incorporating noise attenuation features directly into the fan case, or incorporating active flow control features directly into the fan case, and does not intend to address long-term aging/durability of these concepts.

Within the AvSP, three projects, AADP, IVHM, and IRAC all contain elements of airframe and propulsion health monitoring, diagnosis, and prognosis. The AADP is the only project to develop ground-based methods to detect and characterize damage/degradation, to predict the remaining life and residual strength of degraded components, and to develop mitigation by design or through maintenance processes. AAD technologies will apply the highest-fidelity methods possible and attempt to address damage science at the most fundamental level. AAD will develop time-dependent constitutive models, failure criteria, progressive failure analysis methods, all validated by detailed experimentation. The IVHM and AAD projects have very similar objectives, yet different approaches. AAD technology will enable more durable components and in many cases will rely on periodic inspections. With an IVHM system, inspections will be nearly continuous. Detection/diagnosis technologies developed in IVHM focus on light-weight, ubiquitous sensing such as fiber optics and MEMS, and on near-real-time interpretation of the extracted data, while the analogous technologies developed in AAD are ground-based and include full-field thermography and full-field ultrasonic imaging, processes that are impractical during flight. Similarly, the prognosis technologies in IVHM consider computational speed to be as important as accuracy, whereas AAD technologies are focused on elucidating the details of damage processes and achieving the greatest accuracy possible regardless of computational expense. Finally, mitigation technologies in IVHM are focused on in-situ and real-time mitigation of damage, while the technologies in AAD are oriented toward improving design and maintainability.

The IRAC Project is concerned with severe in-flight discrete-source damage (e.g., resulting from uncontained rotor bursts, missile strikes, or some other unanticipated event) that impacts safety of flight and requires that aircraft control be modified in order to prevent a catastrophic (and fatal) event. Structural damage modeling, analysis, and detection/prediction methods and tools developed in IRAC will be limited to methods applicable to in-flight real time operation. IRAC will leverage damage modeling methods and tools developed by AAD to enable aging effects and material properties to be included in IRAC damage modeling and analysis methods and onboard detection and damage characterization algorithms for control mitigation. Generally, the situations considered within IRAC will be extreme; analysis will be quick and potentially coarse with the sole objective to maintain control of the vehicle and to get to the ground quickly and safely. Both IVHM and IRAC will be developing computationally-efficient methods for onboard prognosis, potentially using AAD-developed predictive tools as a reference solution. It is likely that the analysis methods developed for on-board use could be useful to the AAD project in developing design technology accounting for aging and damage.

2. Milestones and Metrics

2.1 10-Year Roadmap

During an initial planning workshop, the project team drafted a 10-year roadmap for addressing aging-related hazards, using the four-level approach (fundamental science to integrated multi-disciplinary systems) to develop capability in and integrate the three themes; Detect, Predict, and Mitigate. The workshop roadmap was used as a framework for developing the current project content. As described in Section 1.1, eight Challenge Problems were developed with detailed research task plans and resources requirements. The research tasks defined for all of the CPs were collected against the four-level project diagram (Figure 2), to develop the Project Technical Plan Matrix Structure (Figure 3). The planning team then used the task content embedded in the Project Technical Plan to generate a 10-year roadmap for the AADP, shown in Figure 4. This project roadmap is very similar to the workshop roadmap, with some refinement to reflect additional technical details.

The 10-year roadmap represents the progression over time of capability within each box (research area) at each level of the project concept diagram, and the development of fundamental science capability to enable multi-disciplinary capability at the system level. The four-color background separates the roadmap by level: Level 1 to Level 4. The general flow of the 10-year roadmap may be described in the following way. The Level 4 activities consider system level capability, define requirements for technology development at lower levels, and then receive developments as they are produced. The technology requirements filter down through all lower levels. Then, discipline-based building blocks are developed at Level 1 and 2, assembled at Level 3, and validated at the system level, back at Level 4. Looking at the roadmap, it is difficult to identify the flow upward into the three themes (Detect, Predict, Mitigate) because the three themes are overlaid in the roadmap layout. To assist in seeing the development of the three themes, theme-based roadmaps for Detect, Predict, and Mitigate are presented in Figures 6, 7 and 8, respectively. In each figure, only the first five years are shown, and selected milestones are highlighted to display the representative development of capability in each theme. Also, on the right side of the figures, there are arrows pointing to the right with a description of additional development to occur in the out years, i.e., in the second half of the 10-year roadmap.

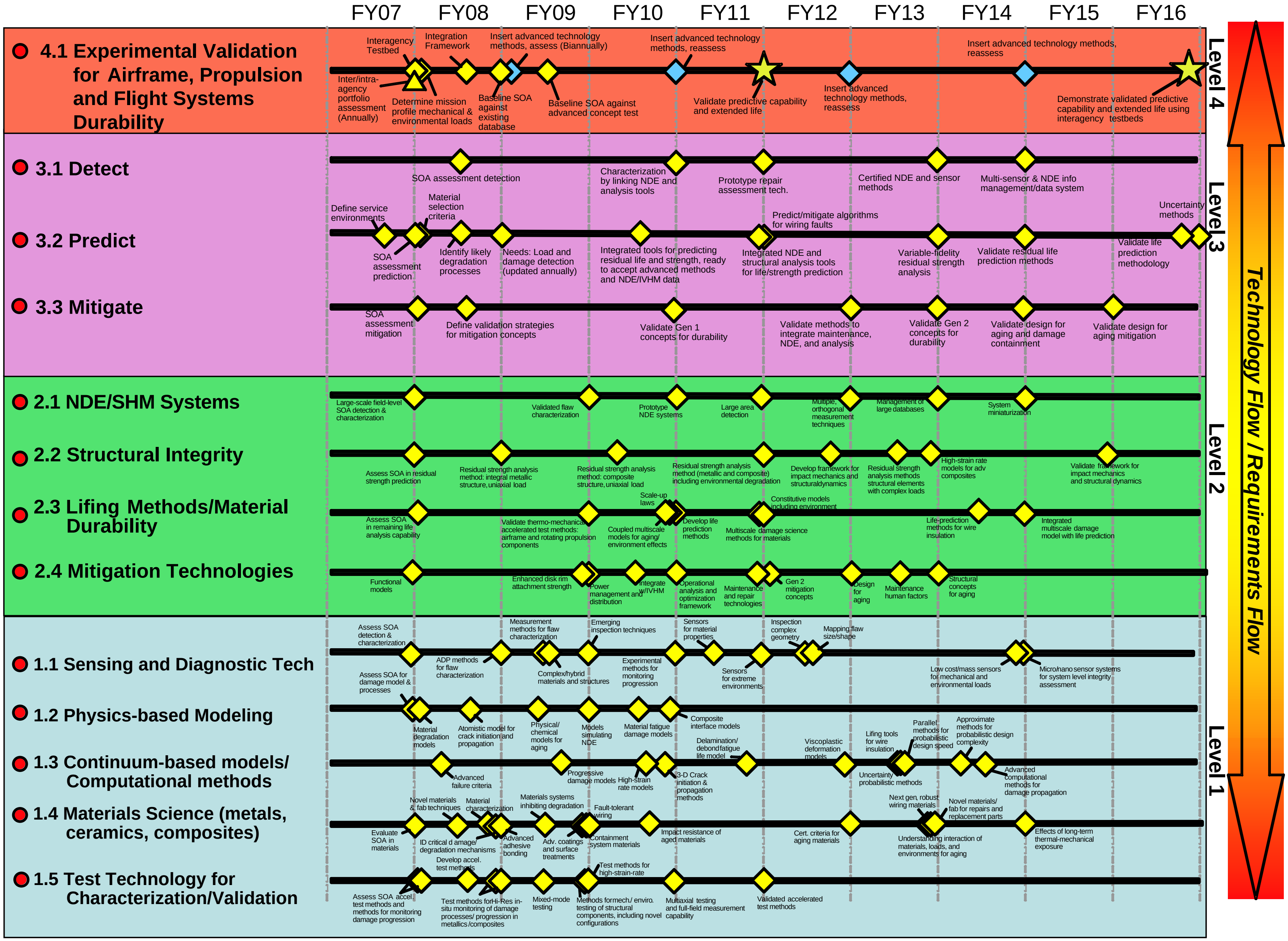


Figure 4. Aircraft Aging & Durability Project 10-year Roadmap.

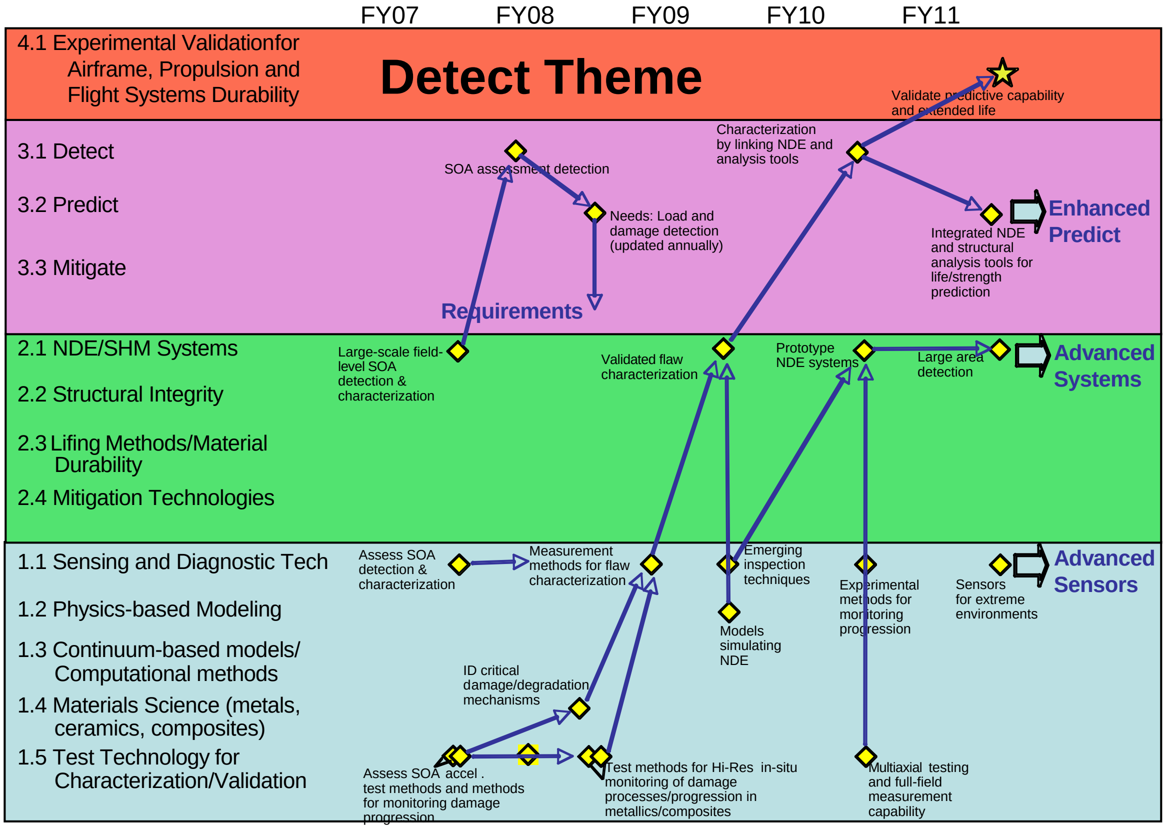


Figure 5. Representative development of capabilities for Detect Theme.

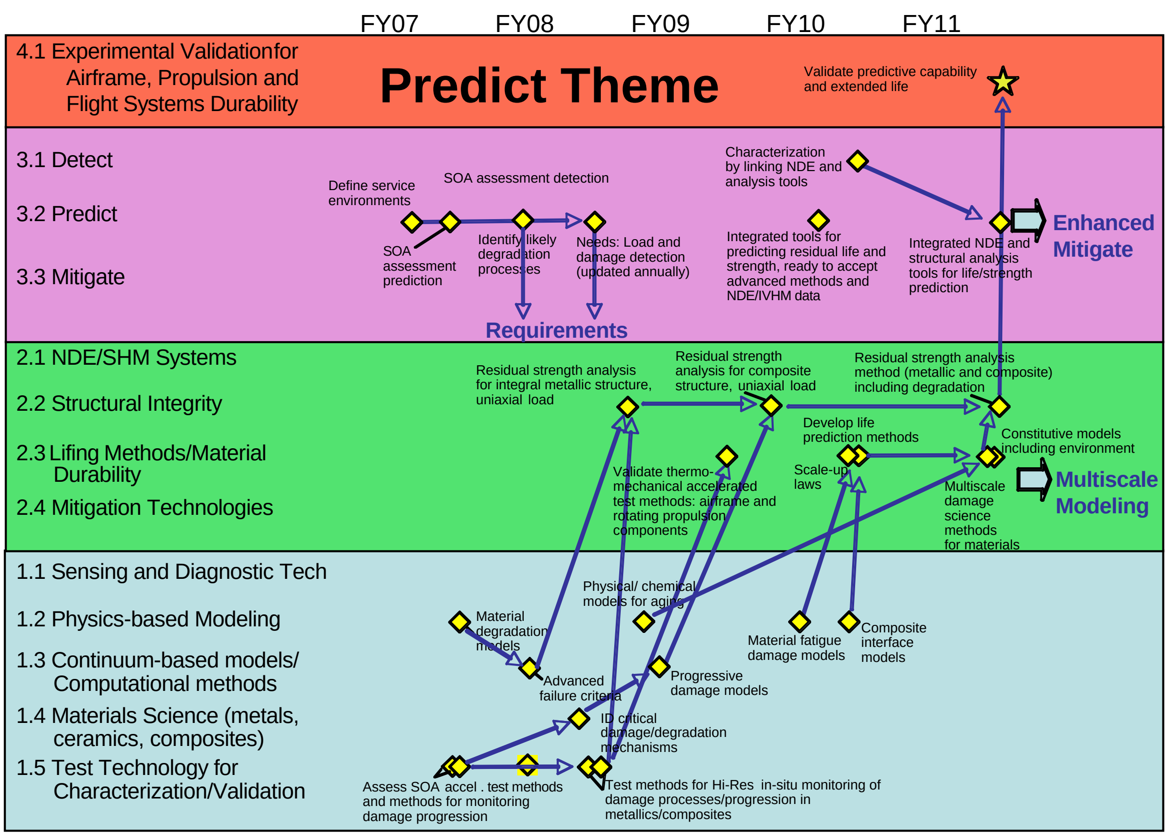


Figure 6. Representative development of capabilities for Predict Theme.

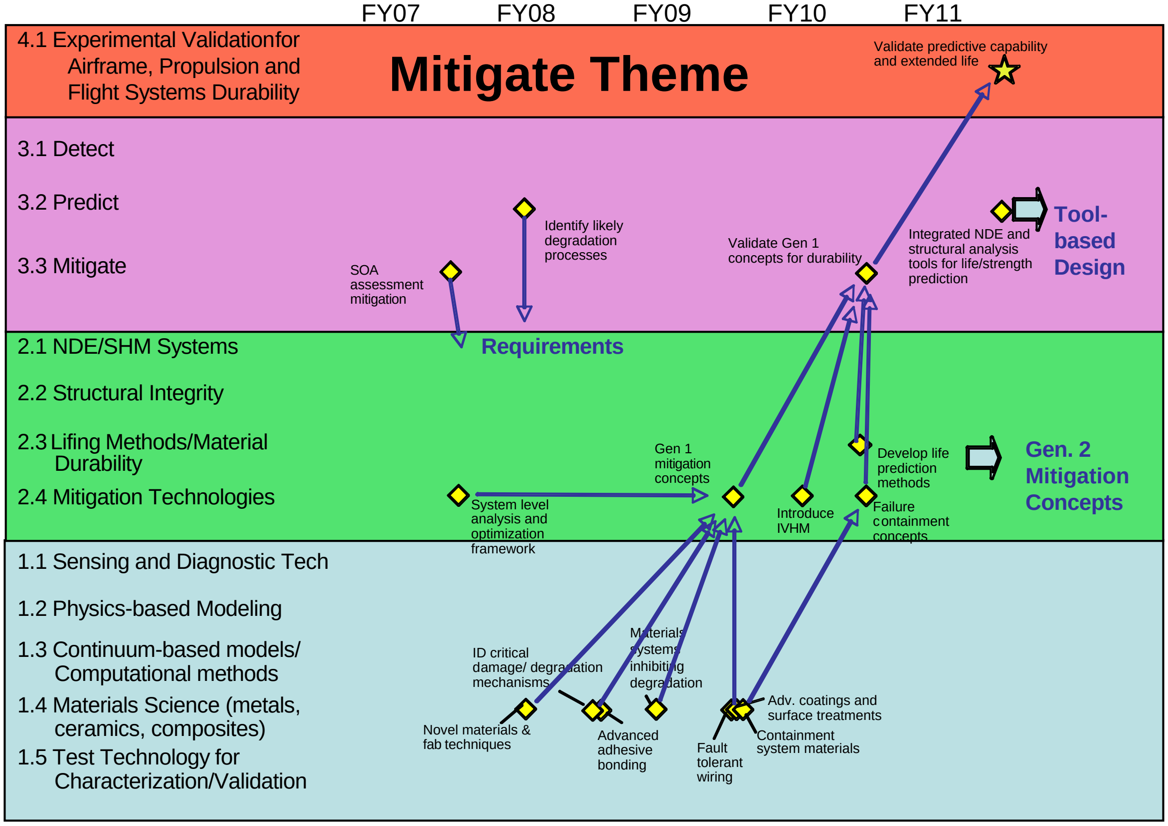


Figure 7. Representative development of capabilities for Mitigate Theme.

2.2 Five Year Milestone Table

Milestones and metrics are defined to enable measurement of progress toward the objectives of the project. The milestones from the first 5 years of the 10-year roadmap reflect the content of the 5-year AADP plan. Detailed descriptions of these milestones, with metrics and dependencies, are listed in Table II. Milestones are presented chronologically along each row in the roadmap. Level 1 milestones are shown first, followed by milestones at Level 2, Level 3, and Level 4.

Note: The AADP considers multiple applications and material systems associated with the various CPs. Some milestones represent an aggregate of application-specific accomplishments, and the milestone date represents the average date of completion. Actual phasing for specific applications will be included in the detailed Project plan. Also, recall that the roadmap milestones are based upon detailed task plans and milestones for each Challenge Problem (see Figure 1, for example). Intermediate milestones from the detailed plans were necessarily omitted from the Project roadmap, but will be included in the detailed Project plan to mitigate risks within the task.

Table II. – AADP Five Year Milestone Listing

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
1.0.00	**Level 1 Milestones**				
1.1.00	**Sensing and Diagnostic Technology**				
1.1.01	Complete coupon/laboratory level SOA assessment for detection and characterization of damage and mechanical and environmental loads	09/2007	Current laboratory SOA detection and characterization capability reported and documented. Define performance criteria for advanced detection and characterization systems.	1.1.03, 1.1.07, 3.1.01	
1.1.02	Advanced digital processing techniques developed for flaw/property characterization	09/2008	Model based processing techniques for flaw/property characterization that can estimate the depth of fabricated flaws in composite structures to within 10% of the actual depth.	2.1.02	1.1.01
1.1.03	Develop measurement methodologies for improved characterization of flaws	03/2009	Measurement hardware that can improve the detection (accuracy and/or speed) of critical flaws in aircraft fuselage, engine and electrical system materials by 15% over level established in 2007.	2.1.02	1.1.01, 1.2.05, 1.5.01, 3.2.05
1.1.04	Develop advanced measurement techniques for complex/hybrid materials and structures	03/2009	Measurement techniques on critical flaws in complex/hybrid materials and structures demonstrated for measurement of bond strength with accuracy within ± 5% of criteria established in 2007.	2.1.02	1.1.01, 1.5.01
1.1.05	Identify/assess emerging measurement techniques that enable improved inspection capabilities	09/2009	Current SOA and emerging technologies identified, assessed, reported, and documented.	2.1.03, 2.1.05	
1.1.06	Develop NDE experimental methods for monitoring damage progression	09/2010	Monitor the growth or progression damage during accelerated aging experiments and verify by destructive testing agreement to within at least 10%.	2.2.04	1.5.02
1.1.07	Develop new sensors methodologies that improve the detectability of flaws and characterization of material properties	03/2011	Refined thin film and nano sensors measurement of aging parameters improved 15% over the criteria established in 2007.	2.2.04	1.1.01, 1.1.04, 3.2.05
1.1.08	Develop sensors and systems for extreme environments	09/2011	Improved high-temperature thin film or nano-sensors for the measurement techniques in hot propulsion environments at temperatures of at least 1100^{o}C		4.1.03
1.2.00	**Physics-based Modeling**				
1.2.01	SOA assessment of current physics based models for damage processes.	09/2007	Current state of the art for deformation and chemical interaction models for metallic and composite materials assessed, reported, and documented. Literature, DoD/Government laboratory methods assessed.	1.2.03, 1.2.04, 1.2.05, 1.2.06, 1.2.07, 2.3.05	

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
1.2.02	Identify critical material degradation processes and develop analytical methods necessary to produce fatigue and fracture models.	10/2007	Critical material degradation processes identified, reported, and documented. Fatigue and fracture models developed within ±10% of the criteria established in 2007.	1.2.03, 1.2.06, 1.3.01, 1.3.02, 2.2.04, 2.3.06	1.4.04, 1.5.02, 1.5.04, 1.5.05, 1.5.08
1.2.03	Develop atomistic models for the initiation and propagation of cracks in metallic materials.	03/2008	Models capable of simulating inter- and intra-granular crack growth developed, dependent upon the appropriate microstructure of the material being examined.	1.2.06, 2.3.04, 2.3.06, 2.3.07, 2.3.08	1.2.01, 1.2.02, 1.5.04, 1.5.10
1.2.04	Develop physical/chemical models for aging effects of metallic and composite airframe materials as well as high temperature metallic materials used in propulsion systems.	02/2009	Atomistic models developed to quantify the effect of 1) water vapor on the potential of metallic about a growing crack tip, 2) water vapor on the deformation of polymer matrix composites, and 3) oxidation on metallic materials in propulsion systems to within ±10% of the criteria established in 2007.	2.3.02, 2.3.03, 2.3.04, 2.3.07	1.2.01, 1.4.02, 1.5.10, 1.5.12
1.2.05	Develop computational models for simulation of nondestructive evaluation techniques.	09/2009	Models for the interaction of selected techniques with metallic and composite airframe materials that predict NDE technique output to within 5% when compared to experimental results.	1.1.03	1.2.01
1.2.06	Develop atomistic models for fatigue crack growth in metallic airframe materials.	02/2010	Atomistic model for fatigue crack growth in metallic airframe materials developed to account for cyclic damage processes to within ±10% of the criteria established in 2007.	2.3.05, 2.3.08, 3.2.08	1.2.01, 1.2.02, 1.2.03, 1.5.04
1.2.07	Develop atomistic models for interfaces in polymer matrix composites.	08/2010	Develop an atomistic model capable of predicting environmental effects on interfaces in a selected polymer matrix composite within 25%	2.2.04, 2.3.05	1.2.01, 1.5.05
1.3.00	**Continuum based models / Computational methods**				
1.3.01	Develop advanced 3D failure criteria for multi-axes loading of (a) aluminum structures and of (b) fiber-reinforced polymer (FRP) laminates.	12/2008	Criteria will predict (a) crack growth initiation load under mixed loading to within ± 10%(b) correct failure mode and failure plane for combined loading conditions.	1.3.02, 2.3.05	1.2.02, 1.4.04, 1.4.03, 1.5.05, 1.5.06

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
1.3.02	Develop progressive crack growth and progressive damage analysis methods for (a) aluminum structures and (b) FRP laminated structures.	06/2009	Analysis tool will (a) predict crack path; crack extension vs. load, ultimate failure load to within ± 15% (b) predict correct failure modes; damage evolution; improve ultimate failure load prediction by x% over the criteria established in 2007. (x TBD dependant on loading condition and failure modes)	2.2.03, 2.2.04, 2.3.05	1.2.02, 1.3.01, 1.4.03, 1.5.05
1.3.03	Develop strain rate dependent deformation and failure constitutive models for FRP composite structures.	08/2010	Predicted high strain-rate stress-strain curve within 20% of measured stress-strain response curve.	2.2.05	1.5.08
1.3.04	Develop 3D finite-element methodology (FEM) for predicting complex crack paths in integral metallic structures	09/2010	Methodology predicts complex crack paths and crack branching in conventional and integral aluminum structure.	2.2.02, 2.2.04, 2.3.05, 2.3.06	1.2.02, 1.3.01
1.3.05	Develop delamination/debond fatigue life model for composite structures	08/2011	Analysis model will accurately predict mixed-mode delamination fatigue response and will predict fatigue life to within ±20%.	2.3.05	1.3.01, 1.4.03, 1.4.04
1.4.00	Material Science (metals, ceramics, composites)				
1.4.01	Evaluate the state of the art in advanced materials	10/2007	Complete and report survey of at least 3 candidate adhesive chemistries	1.4.02, 1.4.05, 1.4.06, 1.4.07, 1.4.08, 3.2.03	
1.4.02	Develop novel materials and fabrication techniques for conducting repairs and fabrication of replacement components	06/2008	Novel hybrid composite with in-plane properties comparable to 2007 SOA, less expensive processing, and 50% improvement in interlaminar properties	2.4.06	1.2.04, 1.4.01, 3.2.03
1.4.03	Material Characterization	08/2008	Strength and modulus data on candidate system in 2 different aging conditions	1.3.01, 1.3.02, 1.3.05, 1.5.08, 3.2.03	
1.4.04	Identify critical damage/degradation mechanisms	09/2008	Critical damage/degradation mechanisms identified, assessed, reported, and documented.	1.2.02, 1.3.01, 2.3.07, 2.4.02	1.5.03, 1.5.04, 1.5.05, 1.5.10
1.4.05	Develop advanced adhesive bonding materials and methods	09/2008	Deliver advanced adhesive with at least 50% improvement in fatigue life under relevant environmental conditions.	2.4.06, 2.4.07	1.4.01
1.4.06	Develop materials systems for inhibition of aging related degradation	05/2009	Matrix resin with 25% reduced moisture absorption	1.4.07	1.4.01
1.4.07	Develop advanced composite materials for containment systems	09/2009	Demonstrate 25% improvement in specific energy absorption from 2007 baseline capability		1.4.01, 1.4.06, 1.4.10, 1.5.08

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
1.4.08	Develop advanced coatings and surface treatments for engine components	09/2009	Advanced coatings and surface treatments for engine components developed to provide inhibition of aging related degradation to ±10% of the criteria established in 2007.	2.4.02	1.4.01, 2.3.07
1.4.09	Develop fault-tolerant wiring network concepts	09/2009	Fault-tolerant wiring network concepts developed to provide improved aging wire characteristics to ±10% of the criteria established in 2007.	2.4.03	
1.4.10	Impact resistance of aged materials for blade containment	02/2010	Demonstrate 80% retention of as-fabricated post-impact load carrying/stiffness	1.4.07	1.5.08
1.5.00	**Test Technologies for Characterization / Validation**				
1.5.01	Assess SOA in accelerated aging test methodologies for composite airframe materials.	10/2007	SOA in accelerated aging test methodologies for composite airframe materials assessed, reported, and documented. Assessment will include composite materials for subsonic environments, critical damage mechanisms, damage indicators, combined effects and test approaches. Comparison of mechanical properties, damage mechanisms with those from long term testing. Literature and DoD/government laboratory databases considered.	1.1.03, 1.2.04, 1.5.03	
1.5.02	Asses SOA for monitoring damage progression.	11/2007	SOA in techniques for evaluating damage processes in metallic and composite structures assessed, reported, and documented. Ability/accuracy to detect and locate fiber damage, matrix damage, and delamination damage assessed. Literature, medical/dental industry, existing and emerging NDE methods considered.	1.1.06, 1.2.02, 1.2.03, 1.2.06	
1.5.03	Develop new accelerated aging and exposure methodologies for structural materials.	05/2008	Methods developed to characterize aging responses in structural materials for critical degradation mechanisms to within ±10% of the criteria established in 2007.	1.4.04, 1.5.12, 2.3.03	1.5.01, 3.2.01
1.5.04	Develop Test techniques for microscopic in-situ monitoring of damage processes for metallic materials	09/2008	Develop load frame capable of applying 1000 lbs. Of force under monotonic or cyclic (at least 1 Hz) while providing high resolution imaging at a crack tip. Specimen must also be imaged using EBSD to provide additional micro-structural information.	1.2.02, 1.2.03, 1.2.06, 1.4.04, 2.4.04	1.5.02
1.5.05	Develop experimental methods for monitoring damage progression in composite materials	09/2008	Validate digital image systems for the measurement of 3D strain fields for composite and integral metallic structure to within 5% of calibrated strain gage measurements.	1.2.02, 1.2.03, 1.3.01, 1.3.02, 1.4.04, 1.5.06	1.5.02, 1.5.04
1.5.06	Develop test specimens/methods for mixed-mode delamination fracture parameters	05/2009	In collaboration with ASTM committee D30 establish test procedures and specimens for delamination characterization. Develop, assess, report, & document.	1.3.01, 1.5.11, 2.2.04	1.5.05
1.5.08	Develop Test technique for high strain rate characterization for adv composite structural concepts	08/2009	Achieve uniform stress/strain at rates up to 1000/sec.	1.2.02, 1.3.03, 1.4.07, 1.4.10	1.4.03

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
1.5.09	Methods for mech./enviro. Testing of structural components, including novel configurations	09/2009	Methods for mech./enviro. Testing of structural components, including novel configurations, developed for measurements within 5% of the criteria established in 2007.	2.2.04, 2.3.02, 2.3.03, 2.3.04, 2.4.03	3.2.01, 4.1.03
1.5.10	Develop test techniques for assessing environmental damage effects on strength and life	09/2009	Environmental exposure must be capable of controlling an environment representative of conditions determined by the study to examine service conditions. Humidity must be controllable to within 5% over duration of a mechanical test.	1.2.03, 1.2.04, 1.4.04, 2.2.04, 2.3.03, 2.3.04	3.2.01, 4.1.03
1.5.11	Establish multi-axes testing and full-field measurement capabilities (including harsh environments)	09/2010	System must be capable of controlling pressurization, axial, hoop and shear loads within 2% of target conditions, while providing temperature and environmental control within 5% of target temperature and humidity.	2.2.04	1.5.06, 3.2.01, 4.1.03
1.5.12	Validated accelerated testing/aging methods	08/2011	Accelerated aging responses compare with long term aging responses to ±10% of the criteria established in 2007.	1.2.04, 2.3.02, 2.3.03	1.5.03
2.0.00	**Level 2 Milestones**				
2.1.00	**NDE / SHM Systems**				
2.1.01	Complete large scale field level SOA assessment for detection and characterization of damage and mechanical and environmental loads	09/2007	Current large-scale field level SOA detection and characterization capability reported and documented. Define performance criteria for large-scale detection systems.	2.1.02, 2.1.03, 2.1.04, 3.1.01	
2.1.02	Develop validated methods for accurate characterization of flaw properties such as size and shape	09/2009	Demonstrate by probability of detection studies the ability to both detect and quantify critical flaws in laboratory specimens to a 95% confidence level.	2.1.04, 3.1.02	1.1.02, 1.1.03, 1.1.04, 2.1.01
2.1.03	Develop and characterize performance of prototypes of advanced NDE systems	09/2010	Publish performance results for new/emerging NDE systems	3.1.03	1.1.05, 2.1.01
2.1.04	Develop and characterize performance of large area systems for damage prediction /characterization	09/2011	Demonstrate inspection of a full-scale structure (wing or fuselage) with sufficient fidelity to detect critical flaws within ±2% of the criteria established in 2007.	3.1.03	1.1.05, 2.1.01, 2.1.02
2.2.00	**Structural Integrity**				
2.2.01	Assess SOA in Residual Strength Methods for Metallic and Composite Structures	09/2007	Predictive capability/accuracy for failure initiation, failure mode and damage progression, and ultimate failure load for metallic and composite materials/structures subjected to uniaxial and combined loads determined. Literature, industry/DoD/government laboratory methods surveyed. Technology gaps in residual strength analysis methods for metallic and composite structures identified. Technology development plan developed.	2.2.02, 2.2.03, 2.2.04, 3.2.02	

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
2.2.02	Develop analysis methods for residual strength on representative integral metallic structural element subjected to uniaxial load	09/2008	Analysis tool will predict crack path, crack growth vs. load, and improve ultimate failure load predictions by 20% over the criteria established in 2007.	3.2.06	1.3.04, 2.2.01
2.2.03	Develop analysis methods for residual strength on representative composite structural element subjected to uniaxial load	12/2009	Analysis tool will predict correct failure modes, damage evolution and improve ultimate failure load predictions by 20% over the criteria established in 2007.	2.2.04, 3.2.06	2.2.01, 1.3.02
2.2.04	Develop residual strength analysis for metallic and composite structures to include environmental degradation	09/2011	Techniques developed for representing aging related degradation mechanisms on material properties and structural geometry in structural residual strength models. Document predicted effect of aging related degradation on residual strength predictions.	3.2.06	1.2.02, 1.2.07, 1.3.02, 1.3.04, 1.5.06, 1.5.09, 1.5.11, 2.2.01, 2.2.03, 2.3.06
2.2.05	Develop a computational framework for impact mechanics and structural system dynamics.	09/2011	Improve prediction accuracy of blade-out event response by 50%		1.3.03
2.3.00	**Lifing Methods/Material Durability**				
2.3.01	Assess SOA Residual Life Analysis Methods for Metallic and Composite Structures.	10/2007	Predictive capability/accuracy for crack growth/damage initiation, crack/damage growth rates and fatigue life for representative loading spectra and environmental conditions determined. Literature, industry/DoD/government laboratory methods surveyed.	2.3.05, 3.2.02	
2.3.02	Validate combined thermal-mechanical accelerated test methods for static propulsion components and for rotating propulsion components.	09/2009	Combined thermal-mechanical accelerated test methods validated for static propulsion components and for rotating propulsion components to within ±10% of criteria established in 2007.		1.5.09, 1.5.12, 2.3.03
2.3.03	Validate combined environmental-mechanical accelerated test methods for airframe components.	09/2009	Combined environmental-mechanical accelerated test methods for airframe components to within ±10% of criteria established in 2007.	2.3.02	1.5.03, 1.5.09, 1.5.10, 1.5.12, 4.1.03
2.3.04	Develop coupled multi-scale models for aging/environmental effects for superalloy disk propulsion components.	09/2010	Down-select commercially available code for the micro-structural aging for superalloy disk material (must display a 2x improvement on grain size prediction and 5% predictive capability on second phase composition).	3.2.06	1.2.03, 1.2.04, 1.5.09, 1.5.10
2.3.05	Develop life-prediction methodologies for refined physics based models for metallic and composite airframe structure and propulsion components.	09/2010	Validate fatigue life of selected metallic and composite components to within ±10% of criteria established in 2007.	3.2.08	1.2.01, 1.2.06, 1.2.07, 1.3.01, 1.3.02, 1.3.04, 1.3.05, 2.3.01, 2.3.06

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
2.3.06	Establish scale-up laws to define required meshing sizes as well as volume of material to model through an atomistic approach about a crack tip in the multi-scale models to provide adequate representation of damage processes.	09/2010	Provide report detailing scaling requirements for selected advanced composite structural materials, scaling requirements / standards for multi-scale models and coupled aging / environmental models.	2.2.04, 2.3.05, 2.3.08	1.2.02, 1.2.03, 1.3.04
2.3.07	Develop constitutive models including environmental effects for presence of pre-existing corrosion damage and the effect of environment on fatigue crack growth.	08/2011	Validate constitutive models by showing fatigue life for pre-existing corrosion pitting and environmentally assisted fatigue within 10% of fatigue life.	3.2.06, 3.2.08	1.2.03, 1.2.04, 1.4.04, 2.3.03
2.3.08	Develop multi-scale damage science methodology for materials using models with embedded atomistic or combined atomistic methods within a continuum model.	09/2011	Validate models by prediction of fracture processes for candidate metallic and composite airframe materials. Predicted fracture loads shall be within 5% of experimentally measured values.	3.2.06, 3.2.08	1.2.03, 1.2.06, 2.3.06
2.4.00	Mitigation Technologies				
2.4.01	Develop functional models for vehicle design	09/2007	Model that incorporates functions of aging components developed with ±10% accuracy of criteria established in 2007.	3.3.02	3.3.01, 4.1.04
2.4.02	Spin test to verify enhanced disk rim attachment strength at component level	09/2009	Enhanced disk rim attachment strength at component level verified to show 10% life improvement over criteria established in 2007.	3.3.03	1.4.04, 1.4.08, 4.1.03
2.4.03	Develop methods for mitigation of aging effects on power management and distribution systems	09/2009	Validated methods for mitigation of aging effects on power management and distribution systems to within 5% of criteria established in 2007.	3.2.07, 3.3.03	1.4.09, 1.5.09
2.4.04	Integrate with IVHM methods to provide damage management capability	03/2010	Damage management capability demonstrated with integrated IVHM capability at the component level to within metric criteria established in 2007.	3.3.03	
2.4.05	Develop operational level analysis and optimization framework	09/2010	Demonstrate application of operational analysis and optimization framework for selected aging mitigation technologies to metric criteria established in 2007.	3.3.03	2.1.03, 2.3.05
2.4.06	Demonstrate validated maintenance and repair technologies at component level.	09/2011	Validated performance of maintenance and repair technologies at component or system level to within metric criteria established in 2007.	3.3.03	1.4.02, 1.4.05
2.4.07	Test second generation adhesive/primer in subcomponent with representative mechanical and environmental loads	10/2011	20% life improvement	3.3.03	1.4.05, 1.4.08, 2.4.02

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
3.0.00	Level 3 Milestones				
3.1.00	**Detect**				
3.1.01	Complete SOA assessment for detection and characterization of damage and mechanical and environmental loads	03/2008	Current SOA detection and characterization capability published as a baseline report. Establish performance metrics for life prediction and repair assessment tools.	3.1.02, 3.2.05, 4.1.01	2.1.01
MS Number	**Milestone Title**	**Date**	**Metric**	**Supports**	**Dependencies**
3.1.02	Develop improved damage characterization analysis tool linked with NDE/Sensor information	09/2010	Demonstrate the linkage of NDE technology with structural analysis tools to successfully predict the remaining life of an aircraft structure to within metric criteria established in 2007.	3.2.06, 3.2.07, 3.2.08, 4.1.09	2.1.02, 3.1.01, 3.2.08
3.1.03	Demonstrate Prototype Repair Assessment Technologies to aid mitigation efforts	09/2011	Demonstrate the ability to inspect an aircraft structure before and after repair and assess the quality of the repair and the integrity of the sub-structure to within metric criteria established in 2007.	4.1.08	2.1.03, 2.1.04, 3.1.01
3.2.00	**Predict**				
3.2.01	Define service environments	06/2007	Provide report detailing service environments (loads and environment) for airframe, propulsion and system components.	1.2.02, 1.5.08, 1.5.09, 1.5.10, 1.5.11, 3.2.04	4.1.02, 4.1.03
3.2.02	Complete SOA assessment for life and strength prediction at system level	10/2007	Provide report for the SOA for life and strength predictions / measurements for airframe, propulsion and systems components. Literature, DoD/industry practices considered.	3.2.05, 3.2.06, 3.2.08, 4.1.01, 4.1.04, 4.1.05	2.2.01, 2.3.01
3.2.03	Define material selection criteria	10/2007	Provide report on detail criteria for the selection of materials for airframe, propulsion and systems.	1.4.02	1.4.01, 1.4.03
3.2.04	Identify likely degradation processes	03/2008	Provide report detailing previously observed aging / failure processes for aged airframe, propulsion and systems and preliminary assessment of critical degradation processes for emerging systems.	1.2.02, 1.4.04	3.2.02, 4.1.03
3.2.05	Perform needs and capability assessment for damage and loads detection (reexamine annually)	09/2008	Determine the required detection capabilities / requirements and the required outputs from predictive and design tools. Assess, report, and document.	1.1.03, 1.1.07	3.1.01, 3.2.02
3.2.06	Develop integrated tools for predicting residual life and strength, ready to accept improved methods and NDE and IVHM input	03/2010	Perform validation tests for inclusion of multi-axial loading on airframe components. Display at least a 20% improvement in prediction from baseline established at start of program.	3.2.08, 4.1.08	2.2.02, 2.2.03, 2.2.04, 2.3.04, 2.3.07, 2.3.08, 3.2.02, 4.1.07, 4.1.09

Table II. – AADP Five Year Milestone Listing (continued)

MS Number	Milestone Title	Date	Metric	Supports	Dependencies
3.2.07	Software algorithms to predict/mitigate wiring faults based on data from NDE technologies.	09/2011	Validated software algorithms based on several testbeds delivered showing results to within 5% of criteria established in 2007.		2.4.03, 3.1.02, 3.3.03, 4.1.09
3.2.08	Evaluate Integrated Structural Analysis/NDE Measurement Capability for Life Prediction	09/2011	Integrated capabilities validated through component level testing of metallic and composite tests showing a life prediction capability that displays at least a 20% improvement in accuracy over existing tools.	3.1.02, 4.1.08	1.2.06, 2.3.05, 2.3.07, 2.3.08, 3.1.02, 3.2.02, 3.2.06, 4.1.07, 4.1.09
3.3.00	**Mitigate**				
3.3.00	**Mitigate**	**3.3.00**	**Mitigate**	**3.3.00**	**Mitigate**
3.3.01	Assess state of the art and state of the practice for mitigation	10/2007	Assess, report, and document.	2.4.01, 3.3.02, 4.1.01, 4.1.04	
3.3.02	Define and develop validation strategies for mitigation methodologies	03/2008	Validation strategies with quantifiable results and time lines for one or more specific system defined, developed, reported, and documented.	3.3.03	2.4.01, 3.3.01
3.3.03	Validate Gen 1 methodologies for durability	09/2010	Gen 1 methodologies for durability using insertion of new design or material at component level validated to within 5% of criteria established in 2007.	3.2.07, 4.1.08	2.4.02, 2.4.03, 2.4.04, 2.4.05, 2.4.07, 3.3.02
4.0.00	**Level 4 Milestones**				
4.1.00	**Experimental Validation for Airframe, Propulsion and Flight Systems Durability**				
4.1.01	Perform inter/intra-agency portfolio assessment for aging aircraft	Annual	Report and document annually.		3.1.01, 3.2.02, 3.3.01
4.1.02	Define interagency testbeds for capability assessment	10/2007	Interagency testbed capability identified, assessed, reported, and documented.	3.2.01, 4.1.03, 4.1.05	
4.1.03	Determine mission profile mechanical and environmental loads	10/2007	Mission profile mechanical and environmental loads identified, assessed, reported, and documented.	1.5.09, 1.5.10, 1.5.11, 2.3.03, 2.4.02, 3.2.01, 3.2.04	
4.1.04	Develop framework integrating detect, predict and mitigate, and insert SOA methods	03/2008	Framework developed for integrating detect, predict and mitigate, and inserting SOA methods with characteristics to within 10% of criteria established in 2007.	2.4.01	3.2.02, 3.3.01
4.1.05	Establish baseline of predictive capability on: Legacy system test or existing database	09/2008	Baseline of predictive capability established, reported, and documented.		3.1.01, 3.2.01, 4.1.02

Table II. – AADP Five Year Milestone Listing (concluded)

4.1.06	Insert advanced technology methods and assess	09/2008	Advanced technology methods insertion assessed, reported, and documented.	Intermediate milestones to be assessed not captured using level of detail in this table	
4.1.07	Establish baseline of predictive capability on: Subscale advanced concept	03/2009	Baseline of predictive capability on subscale advanced concept established, reported, and documented.	3.2.06, 3.2.08	
4.1.08	Insert advanced technology methods and reassess	09/2010	Advanced technology methods insertion re-assessed, reported, and documented.		3.1.03, 3.2.06, 3.2.08, 3.3.03
4.1.09	Demonstrate performance with mitigation effort applied: predictive capability and extended life using interagency testbeds	09/2011	Predictive capability and extended life using interagency testbeds demonstrated for 50% improvements over criteria established in 2007.		3.1.02, 3.2.06, 3.2.07, 3.2.08

3. Technical Approach

The following section addresses the technical approach and feasibility of accomplishing the research milestones listed in Table II. The technical approach is based upon NASA's long history in structures and materials research. The skills required to complete the research tasks are within NASA's core competencies. The research team assembled for the AADP has expertise in airframe, propulsion, wiring systems, metallics, composites, NDE, sensors, and systems analysis. The technical approach is described relative to each row in the roadmap (Figure 4). The Section title and number in parenthesis corresponds to the roadmap row designation.

3.1 Level 1 – Fundamental Science

3.1.1 Sensing & Diagnostic Technologies (1.1)

As material systems and structural components advance, there is a growing need for improved sensing and diagnostic technologies that can characterize damage and quantify relevant material properties. New structural fabrication methods also result in the need for advanced inspection capability to detect critical flaws. For example nondestructive evaluation (NDE) was mentioned repeatedly in the Columbia Accident Investigation Board report as critical in assuring Space Shuttle and Space Station safety, and has been cited as needing more resources and development. NDE was in the critical path for impact testing of the thermal protection system required for Shuttle return to flight and it has been a core discipline at the NASA Engineering and Safety Center since that organization's inception. During both the NASA Aircraft Structural Integrity Program (NASIP) and Shuttle Return to Flight (RTF), both Langley and Glenn Research Centers developed significant NDE capabilities and research facilities that can now be utilized to address the needs of both legacy and emerging aircraft and engine materials. In order to enable technologies that will effectively manage the aging of aircraft materials and structures it is essential that fundamental research support the advancement of current NDE capabilities to meet increasing inspection challenges. Additionally, new and emerging technologies must be pursued and matured to address shortfalls of conventional methods.

The fundamental science necessary for successful development of sensing and diagnostic technology is initially the development of advanced signal processing methodologies for the characterization of flaws in both legacy and emerging materials and structures. These methodologies grow from developing a clear understanding of the basic physics involved in performing an inspection as well as developing physics-based models to characterize the interactions of energy with materials on a fundamental level (see Section 3.1.2). Once developed, these processing techniques can then be applied to both current state-of-the-art (SOA) technologies and to emerging techniques. In order to fully understand the capabilities and shortcomings of the current technology for the problems associated with managing the aging of aircraft structures, a SOA assessment will be performed. To effectively link detection and prediction technologies to analysis tools it is important to consider both damage and mechanical and environmental loads sensing technology in the assessment. Additionally, Ames Research Center has the capability to use the SOA assessment as a basis for developing tools to assess the risk associated with the NDE technologies targeted for development to provide enhanced mitigation capability.

Many of the existing NDE technology concepts rely on the isotropic behavior of the material being inspected. Legacy and emerging materials, such as fiber-reinforced composites and some metals, have relatively strong anisotropy of physical properties. For example, the ultrasonic wave speed varies by nearly an order of magnitude with direction relative to the fibers in some composites. To successfully develop NDE technologies for these materials it is important to develop advanced digital processing (ADP) methods to extract as much information as possible from existing inspection techniques. Coupled with the ADP methods would be continued development of advanced technologies. For instance, ultrasonic (UT) phased arrays are being employed to improve measurement speed and information content. While many advances have been made in applying UT arrays for medical applications, considerable research is required to expand their use to materials with high anisotropy. LaRC has unique capabilities in the UT Phased Array Test-bed (UPAT) system that can be used to develop the measurement and analysis techniques necessary to apply this technology to aircraft materials. Likewise, thermographic and terahertz imaging technologies have achieved a significant level of maturity in inspecting homogenous materials, but little research has been done in extracting important material and flaw information in anisotropic materials that are emerging in aircraft structures. Other NDE technologies such as guided wave ultrasonics, liquid-crystal display based full-field ultrasonic imaging, acoustic testing, conventional and modal-acoustic emission, and shearography may be considered. Further, many NDE techniques have historically been used for flaw detection, but have shown promise for much greater application. One such technique is non-linear ultrasound, which has shown potential for both bond strength and metallic fatigue measurements. LaRC researchers have begun developing the fundamental science necessary to make these measurements; continued development in this has the potential to transition the science into tools necessary for evaluating material aging.

Determining the remaining life of electrical systems, such as aircraft wiring and electrical insulation, is an area where little research has been performed. With the advent of technology such as “fly-by-wire,” electrical systems are becoming increasingly critical. Emerging technologies, such as lamb-wave ultrasound and effluent based inspection (US Patent No 6,838,995 B2 awarded to NASA LaRC), have shown the ability characterize wire insulation. Research to mature these technologies to assess wire aging and to predict when repair or replacement is a necessary step in preventing age related electrical system failures.

3.1.2 Physics-Based Modeling (1.2)

Classical fracture mechanics is based on the comparison of computed fracture parameters to their empirically determined critical values. Although this approach has been extremely successful for modeling crack growth at structural scales, it does not describe the fundamental processes that govern fracture. Ultimately, an understanding of events and processes that occur at length scales on the order of 10^{-9} to 10^{-3} m is needed to understand crack growth and circumvent the limitations of empirically determined extrinsic metrics such as G_c, J_c, CTOA, etc. Emerging computational technologies such as discrete atomistic molecular dynamics (MD) simulations, multi-scale modeling, and various continuum mechanics-based micromechanics analyses (including finite elements (FE), and meshless local Petrov-Galerkin methods (MLPG)) are contributing to a new paradigm for understanding damage processes in structural materials - *computational damage science.*

Through the development of discrete atomistic molecular dynamics simulations, one may model the effects of microstructural features on damage evolution. Consequently, it is critical to identify representative damage processes for select materials to be modeled. Details on the methods to identify damage processes are detailed in Section 3.1.4. As physics-based models describing damage processes are developed, experimental validation will be performed.

<u>Metallic Materials</u> Fracture is a local and highly material specific phenomenon. In general, failure processes are different for every material system or class of material systems. For example, in 7075 aluminum, fatigue damage is known to initiate at the interfaces of iron containing precipitates present near grain boundaries. In contrast, fracture in 2024 and 7050 aluminum alloys tends to initiate along grain boundaries. Understanding of these and other material-specific damage mechanisms is a crucial step toward developing more robust continuum-scale failure criteria and is a necessary foundation for engineering of materials. To develop and validate these new predictive capabilities, it is critical to examine metallic materials of varying levels of micro-structural complexity. Materials to be examined include fine and coarse grain aluminum, aluminum copper binary alloys with and without second phase particles, and age hardenable aluminum alloys with and without second phase particles. When possible, these material systems will be acquired commercially; however, this program will also have access to the extensive materials processing capabilities at LaRC to produce specimens of specific microstructure for interrogation. These materials will be examined and tested using the in-situ testing system described in Section 3.1.5. Here, the microstructure of each specimen will be characterized and used as the basis of the atomistic model. The propagation of damage will then be predicted using the physics-based model and compared to the propagation of damage observed for the test within the scanning electron microscope (SEM). Due to the scale of the damage processes being modeled, it is necessary to also examine the damage processes experimentally on such a scale in order to validate the predictive capabilities to be developed.

<u>Composite Materials</u> Aging of polymer matrix composites involves molecular-level processes (such as chemical interaction with moisture), microscale processes (such as changes to the fiber/matrix interface), as well as meso-scale effects (such as matrix cracking). Mitigating the effects of aging through new materials introduction will require understanding of the molecular origins of physical changes. This understanding will be obtained through molecular mechanics and dynamics simulations of epoxy resins and of their adhesion to graphite fibers. The suitability of available interatomic potentials will first be evaluated against small-specimen data (Section 3.1.4). If necessary, new quantum-chemically-derived potentials will be created. Current research at LaRC has shown how the macro-scale consequences of local effects (those that occur on the scale of a few nm) can then be predicted. An atomistically-detailed representative volume element (RVE) containing a few thousand atoms can be simulated, usually with periodic boundary conditions. An equivalent continuum description of the RVE is then obtained by deforming the volume and calculating deformation energies. The continuum description will then be incorporated into micromechanical models.

<u>Chemical Aging Effects</u> The effect of strain on the mechanical behavior of materials is not the only physics-based tool for the study of damage processes. Recent work on molecular reaction analysis has been used to model the effects of adsorbate-surface interactions for transition metals. These processes are the same processes observed when structural metallic materials are exposed to aggressive environments. Such processes affect the behavior of the metallic material in the region of the crack tip thereby affecting damage propagation. Since such work is outside

of the technical scope of this plan, it would be advantageous to identify this area of study for cooperative partnership through an NRA task. It is also believed that such models may be applied to the development of new atomistic potentials for the material about a crack tip exposed to an aggressive environment. If so, this work may be the basis for the development of a physics-based approach to such environmentally assisted cracking problems such as corrosion fatigue and stress corrosion cracking (SCC).

<u>Thermal Aging</u> Engine disks are exposed to elevated temperatures when in operation. Consequently, the superalloy materials used to fabricate these components may undergo thermal aging resulting in second phase precipitation and potentially grain growth. As these materials age, their mechanical behavior may be adversely affected, thereby affecting the safe use of these materials in propulsion systems. It is desirable to develop a better understanding of the aging processes of these materials in the typical service environments, to more accurately predict the useful life of these components and to assist in the development of new material chemistries and microstructures that will not be susceptible to such aging effects. Commercially available thermodynamic codes are becoming sufficiently refined to address this problem. Several codes will be evaluated by comparing results from these analyses with historical information for disk materials. Following this technical evaluation, the most suitable system will be purchased for use in this project.

3.1.3 Continuum-Based Models and Computational Methods (1.3)

Analysis and modeling techniques are valuable in the process of understanding the fundamental aging characteristics of materials and in assessing the structural residual strength and durability of structural components fabricated from these materials. Aging-related and other degradation mechanisms can operate over a broad range of structural scales, ranging from atomistic to macroscopic. Research at the fundamental science level is necessary to develop models at the various structural scales (atomistic, micro-, meso-, macro-level) in order to better understand the degradation mechanisms and their effect on structural performance, and to predict accurately the durability and residual strength of complex aerospace structures.

Continuum-level (meso- or macro- level) models and methodologies are appropriate for large-scale structural component computations. Development of continuum-level models will leverage the products of previous research programs and the increased understanding of damage mechanisms obtained through fundamental research conducted in "Physics-Based Modeling" (Section 3.1.2) and "Materials Science" (Section 3.1.4).

<u>Metallic Structure</u> During the 1990s, under the NASA Airframe Structural Integrity Program (NASIP), NASA Langley Research Center (LaRC) conducted extensive research on the fracture behavior of thin-sheet aluminum alloys. Two of the products of that research are the constant critical crack-tip-opening angle (CTOA) fracture criterion, and a high-fidelity residual strength analysis methodology for thin-skin aluminum fuselage structures with cracks and subjected to combined internal pressure and mechanical loads. The residual strength analysis methodology is based on the CTOA fracture criterion and the STAGS nonlinear shell finite element code. The methodology is applicable to complex built-up structures, and accounts for combined loads, geometric nonlinearity, and material nonlinearity associated with elastic-plastic fracture. Although the analysis capability developed during the NASIP program represents a significant advancement in residual strength analysis capability for aluminum fuselage structure, additional enhancements to the methodology are needed to address mixed-mode loading conditions and

three-dimensional effects associated with general curvilinear crack growth in integral and thick-skin metallic aircraft structures.

A combined experimental-computational approach aimed at understanding and predicting ductile fracture in aluminum aerospace materials is planned. A methodology based upon a macro-level fracture criterion, like the CTOA criterion, will be developed and implemented in a three-dimensional (3D) finite-element framework for predicting complex crack growth paths and crack branching in integral structure. Additional research is needed to develop ductile mixed-mode 3D fracture theories that govern crack growth and crack-growth trajectory in selected airframe aluminum materials. Development of the fracture theories is outside of the scope of this plan and is recommended as a topic for university collaboration.

Experimental studies of damaged structural elements, and damaged integrally stiffened structures will be conducted to develop and validate the analysis methodologies and the general 3D fracture criterion. Existing video-image correlation capabilities at NASA Langley will be used to quantify three-dimensional deformation, including crack-tip displacements during crack growth.

<u>Composite Structure - Continuum Damage Mechanics Models</u> Structural failure in composite materials is the result of a process of accumulation of damage mechanisms such as matrix cracking, fiber-matrix separation, fiber fracture, fiber kinking, and delamination. To develop robust methods that can predict the strength and damage tolerance of advanced composite structures, it is necessary to account for the evolution of damage modes and the corresponding redistribution of internal loads. Considerable research has been conducted in composite damage. However, there still remains significant uncertainty in the prediction of composite failure, as indicated by a recent World Wide Failure Exercise (WWFE). The results of the WWFE indicated that the prediction of most classical failure theories differ significantly from each other, and from experimental observations, even when analyzing simple laminates.

An analytical nonlinear constitutive model based on continuum damage mechanics (CDM) and fracture mechanics will be developed to represent intralaminar damage onset, and damage propagation in advanced composite structures. Damage activation functions for representing damage onset will be based on the LaRC03-04 failure criteria previously developed at LaRC. These criteria are a set of six phenomenological failure criteria for fiber-reinforced polymer laminates and have been demonstrated to predict matrix and fiber failure accurately for selected loading conditions. The constitutive model will be implemented in an efficient subroutine for incorporation into finite element simulations. The model will overcome some of the problems with existing CDM models including insufficient demonstration of thermodynamic consistency, lack of regularization of the energy dissipation after damage localization, and inability to account for residual stresses. In addition, the constitutive equations will be explicitly integrated in the model formulation to achieve the computational efficiency required to perform large-scale structural computations.

To model both intralaminar and interlaminar damage progression in structural analyses, models for intralaminar damage, such as the CDM model to be developed, can be used with models for representing interlaminar damage, such as decohesion elements. In some situations, with the current technology, intralaminar damage models do not have the correct interaction with interlaminar damage models. Investigation of approaches to account for damage mode interaction is outside the scope of the current plan, and is recommended as a topic for university collaboration.

Experimental studies of pristine and damaged structural elements subjected to uni-axial and load will be conducted to validate the failure criteria and the nonlinear constitutive models. Existing video-image correlation capabilities will be used to quantify three-dimensional deformation and to monitor surface indicators of damage propagation. X-Ray and other NDE techniques will be investigated/developed to monitor progression of internal damage (see Section 3.1.5). Additionally, the damage processes observed for selected materials systems will be characterized.

Composite Structure – Fatigue Damage Models Mechanical fatigue is a common cause of failure of aerospace structures. In metallic structures, damage tolerance has been demonstrated using fracture mechanics to characterize crack growth under cyclic loading and to establish inspection intervals and non-destructive test procedures to ensure fail safety. In composite structures, delamination is the most common macroscopic damage mechanism, and several efforts have been undertaken to develop a similar damage tolerance approach for composite materials by characterizing delamination growth using fracture mechanics. Full implementation of fracture mechanics in the design of composite structures requires advancements in delamination growth prediction, improvements in delamination growth criteria under mixed-mode conditions, including development of characterization specimens, and consideration of three-dimensional geometry and out-of-plane loads.

A continuum damage mechanics fatigue model based on cohesive laws to predict progressive delamination/debonding of airframe components will be developed. The model will build on decohesion element technologies previously developed at LaRC for delamination growth prediction. In addition, limitations in life prediction criteria will be identified and assessed. In particular, the accuracy of selected mixed-mode delamination onset criteria, the development of the fracture interaction diagram, the validity of combining mode II and III in three-dimensional analysis, the definition of mixed-mode growth criteria, and the consideration of spectrum loading criteria will be evaluated. Research will also be conducted in collaboration with ASTM committee D30 to develop characterization tests for determining critical fracture parameters for mixed-mode conditions.

3.1.4 Material Science – Metals, Ceramics, Composites (1.4)

Many different approaches could be used to mitigate aging-related effects -- changes to aircraft maintenance and operations, for example. The most basic approach, however, is to choose or insert materials that are inherently less susceptible to the effects of time, environment, or loads. Thus the materials science of aging, including new materials development, has an important place at the Fundamental Science level of AADP. The work falls into three categories: new materials, materials aging, and failure analysis.

New Materials Although carbon fiber composites are finding their way into primary transport aircraft structure, design for the combined effects of time, load, and environment is currently beyond reach. In addition, metal/organic hybrids (like GLARE) have a special role in next-generation aircraft; we plan a more versatile fabrication method that may increase the usefulness of the hybrids. Damage containment systems such as those used to contain engine fans must be able to withstand dynamic loads at any point in their life, yet little is known about how they age. Previous materials synthesis work at both NASA LaRC and GRC has centered on adhesives or composite matrix resins with resistance to oxidative aging (ACT, HSR) and fire (Aviation Security). This new research program will focus on 1) durable new adhesive/matrix resins

2) hybrid laminates and 3) composite containment structures of fiber pre-form architectures and their potential degradation.

It is known that epoxy resins absorb moisture and that moisture both plasticizes the resin and decreases the transverse strength of a lamina. The research will aim to mitigate these effects by quantifying the influences of resin chemistry, network structure, and stress on hygrothermal aging, and further, to use that knowledge to plan new resin compositions. The approach will be to formulate a molecularly-based model that incorporates the relevant variables and validate it via aging of small coupons of model resin compositions. The model can then be "inverted" to predict the relative importance of each variable and design a new resin. The work will be linked to physics-based structural models (for loads) and, ultimately, to multidisciplinary design tools.

Metal/organic laminates potentially provide design flexibility by improving both fatigue and impact durability relative to single materials. We plan to synthesize hybrid panels via simplified processing routes. In-plane properties should be tailorable and the process may provide some degree of through-thickness reinforcement. Early delamination and fatigue testing will be tailored to prove or disprove this conjecture. If properties are at least equivalent to existing commercial forms, work will then turn to exploring the limits of the process (principally layup and curvature) to deliver advanced architectures.

Candidate newly-developed containment structures built from fiber pre-form composite material systems will be subjected to accelerated aging; the effects of aging on material properties will be determined by high strain rate testing using methods developed in this program. In addition, the damage processes and integrity of these containment systems as a function of aging condition will be characterized. The results will inform continuing work at the subsystem (case) level.

<u>Materials Aging</u> Experimental aging data are critical for characterization of damage processes and for assessing and validating models of the long-term performance of materials in complex service environments. Long-term and accelerated testing (see Section 3.1.5) will be conducted on candidate materials. This will both establish a durability database useful for material screening (preliminary design) and quantify degradation processes (degradation/damage mechanisms and signatures). Both will be useful for validation of models developed under the "Predict" theme. In order to minimize the testing requirements, the data relevant to model development and validation will be identified prior to establishing the test program.

New high-temperature (i.e. nickel-base) superalloys and processing technologies enable higher engine disk operating temperatures leading to improved performance and/or specific fuel consumption in subsonic aircraft. Long term durability and aging characteristics of these new materials must be understood and addressed to prevent potential fleet problems five or ten years from now. Of particular concern is the fatigue durability at rim attachment features. We plan to study the long term, notch fatigue capability of next generation powder metallurgy disk alloys such as ME3, Alloy 10, and LSHR. Various heat treatments will be assessed (in the virgin state as well as the aged state) to determine which combination of alloy and heat treatment yields the optimal notch fatigue strength while still maintaining the required strength and creep capability at representative (1300 °F) rim temperatures. Other issues, such as hot corrosion and microstructural instability, will be integrated into this task to help understand the effect of long-term degradation on notch fatigue strength.

The higher operating temperatures enabled by the new class of turbine disk alloys have substantially increased the influence of hot corrosion damage mechanisms. Ongoing work in the

Propulsion 21 program has shown that the low cycle fatigue life debit due to hot corrosion attack can result in an order of magnitude reduction in fatigue life. Microstructural damage models will be developed to characterize and predict this debit, taking into consideration local stress concentrations due to corrosion induced artifacts such as pitting. In order to mitigate corrosion damage, novel surface treatments that impart deep residual compressive stresses (such as Low Plasticity Burnishing and Laser Shock Peening) will be identified, fully characterized and modeled. Novel ductile noble metal coatings will also be tested to determine their suitability to act as hot corrosion barriers.

In addition to environmentally induced surface attack, high temperature exposures during service can produce microstructural changes within the bulk of the material. Gamma prime precipitates take up 50+ volume percent in modern disk superalloys. Not only the precipitate volume fraction, but also the size and shape of the precipitates strongly influence strength, creep, and fatigue crack growth resistance. The gamma prime characteristics are initially set by heat treatment of the disk. Therefore, disk material with at least two different heat treatments will be exposed for various times; changes in gamma prime sizes will be quantified, as well as changes in mechanical properties, and models will be generated to track and predict these changes. Service exposures at high temperatures can also encourage the precipitation of additional phases, some of which, such as those in the topologically close packed class, have acicular or plate morphologies that can produce stress concentrations. The precipitates may also have higher strength and lower ductility than the superalloy matrix, so they can promote premature crack initiation in tensile, creep, or fatigue loading. These issues will also be addressed by exposures of disk material and models will be generated, using commercial software packages where available, to track and predict the precipitation and effects of these potentially harmful phases.

<u>Failure Analysis</u> Understanding the damage sustained during actual operations -- due to mechanical loading, corrosion, or their combined effects -- is critical to the development of improved predictive tools, non-destructive detection methods, and methods to mitigate the initiation of damage processes. NASA Langley has had strong partnerships with the Air Force Research Laboratory, the FAA, and the Shuttle Program Office for several years and has examined components removed from military, commercial and space vehicles. Damaged components will be inspected with optical and scanning electron microscopy and with Fracture Surface Topographical Analysis (FRASTA), in which a confocal laser microscope is used to produce three-dimensional topographical maps of conjugate fracture surfaces. The maps are then matched and the fracture process is simulated to gain a better understanding of the creation of the failure surfaces. Application of this technique to polymer matrix composite materials will provide better insight into the evolution of damage and into failure criteria applicable to predictive models for structural integrity. Video Image Correlation (VIC) has been successfully applied to the examination of metallic and composite test articles. Images are acquired during mechanical testing to produce either two- or three-dimensional strain maps of the specimen surface. Such data are vital to understanding damage progression, particularly in built up structure.

Corrosion is traditionally treated as a uniform loss of material from a component; pitting damage, however, can act as a local stress concentration and promote fatigue crack initiation. Discreet pits produced in lap splices of airframe materials and along leading edges of propeller materials can result in the initiation of fatigue cracking. Representative pitting damage will be produced on specimens of selected materials. The morphology of the pitting damage will be characterized. Fatigue life testing will then be performed using loading conditions representative for either fuselage skin or propeller applications. A data base of the relative notch fatigue sensitivity as a function of pit size and morphology will be generated. From this data, a first-of-its kind analysis will be performed to determine pit sensitivity as a function of pit morphology. Such an analysis is critical when examining the effectiveness of new materials and dissimilar metal joints. Under the standard approach, a new database must be generated for each new material. However, if models to account for the morphology of pits are developed one can assess the effect of existing pits on fatigue life, by simply evaluating the pitting characteristics for a new material. Such a method will also be instrumental in evaluating new joints or the performance of metallic components in hybrid laminate structures. The joining of dissimilar metallic and composite components can result in accelerated localized corrosion processes. This makes it critical to understand the effect that localized corrosion can have on fatigue life of such material systems.

3.1.5 Test Techniques for Characterization and Validation (1.5)

An improved understanding of damage accumulation processes in aerospace materials and improvements in structural integrity and life prediction methods require development of several novel test capabilities and methodologies to characterize damage processes and material behavior and to validate predictive tools. Test capabilities to be developed include: an in-situ loading capability in a scanning electron microscope (SEM) for the characterization of damage processes, combined loads testing capabilities for the evaluation of structural components subjected to realistic flight loads, NDE methods for in-situ monitoring of damage progression, accelerated testing and exposure approaches for characterizing aging effects in metallic and polymer matrix composite materials, and test techniques for high strain-rate characterization of composite materials systems.

<u>In-Situ Damage Monitoring</u> In-situ loading capabilities will be developed in an Environmental Scanning Electron Microscope (ESEM). Here the initiation and propagation of damage under the combined effects of load (monotonic and or cyclic) and environment (water vapor and condensed water) can be characterized. This system is equipped with Electron Back-scattered Diffraction (EBSD), to characterize the effects of microstructure on crack propagation in metallic materials. Here the microstructure about a crack tip will be characterized and the crack path and dynamic crack growth rate of the propagating crack can be determined. Such tests will not only be used to characterize fatigue and fracture processes of materials to aid in the development of life prediction and structural integrity tools, but are critical for validating emerging physics-based models. Over the last ten years, video-image correlation techniques have been developed to provide non-contacting displacement and strain field measurements for components of various geometries as they are deformed. The Aircraft Aging and Durability Project would like to identify a partner to develop similar video-imaging techniques for application to in-situ SEM tests. Such a capability would make it possible to identify the strain local to micro-structural features, which is critical to the development and validation of accurate physics-based damage models.

Imaging techniques will also be developed for in-situ monitoring of damage initiation, damage accumulation and damage propagation in composite structural test specimens under load. Video-image correlation techniques will be investigated for monitoring near surface damage progression, and for monitoring local strain gradients and load redistribution associated with internal material failures. NDE techniques such as X-Ray, micro-CT, ultrasonic and thermographic imaging technologies will also be investigated for monitoring accumulation of internal damage. Test capability development will be closely integrated with Sensing and Diagnostic Technology development (Section 3.1.1) to ensure efficient development of the test technology. These capabilities are essential to increase understanding of damage processes in composite structures and to the development and validation of progressive damage analysis methodologies for composite structures.

Combined Loads Testing The safe use of composite and integral metallic structure on future aerospace vehicles will require an improved understanding of their fatigue and fracture behavior under combined loads. Two test beds are under development at LaRC for combined-loads testing. A unique testing facility for combined torsion, bending, shear and internal pressure will enable the simulation of relevant flight conditions for curved structural panels and cylindrical shells. A biaxial loading frame will also be developed for investigating the structural and failure responses of flat un-stiffened and stiffened panels. These test capabilities are necessary to examine the complex damage accumulation and damage propagation processes in built-up structures subjected to combined loads that may not be represented accurately by uniaxial test conditions. In addition, complex multi-axial loading conditions must be considered to assess modeling assumptions and to establish the range of validity of computational models.

Effects of Aging on Composites The wide scale use of composite structure in airframes is fairly new, particularly on commercial airframes. In order to anticipate aging related damage in composite structures that will be observed after some time in service, accelerated testing and exposure approaches must be developed to induce characteristic damage under the combined effects of load and environmental exposure. Development of these methods will first require defining the service environment and identifying damage mechanisms and synergistic load and environmental exposure effects that will most likely result in degradation of structural properties. Test methods to evaluate material responses for individual damage mechanisms acting alone are fairly well established. However, the possible synergistic effects of multiple mechanisms are not well understood, and are difficult to establish under accelerated conditions because the relationship between accelerated and service conditions is often different for different damage mechanisms. In order to develop accelerated aging approaches the mechanisms that underlay aging in polymeric material systems must be understood and will be explored by long-term testing and through analytical studies using validated physics-based models developed in Section 3.1.2. Accelerated test approaches will be validated by comparing mechanical properties, damage mechanisms, and physical parameters (e.g. weight loss, changes in glass transition or fracture toughness) from accelerated testing with those from long-term laboratory testing data, and in-service data, where available.

High Strain Rate Testing Improved methods to analyze the response of polymer matrix composite structures under high strain rate impact conditions will be developed. As part of this process, existing test data will be cataloged and the status of existing NASA and Boeing modeling methods will be evaluated. Experimental techniques will be developed on the coupon level and tests will be conducted on materials representative of aircraft engines containment case structures in order to characterize fully the material deformation/failure constitutive models. Ballistic impact tests will then be conducted on subcomponents (i.e. flat and cylindrical panels) and full-scale prototype containment case structures in order to provide data for verification analyses, which will be conducted using LS-DYNA and the newly developed and implemented material models.

3.2 Level 2 – Discipline Level Capabilities

3.2.1 NDE / SHM Systems (2.1)

To effectively inspect the structures associated with commercial aircraft, it is necessary to develop NDE systems capable of characterizing materials over large areas, such as a complete fuselage, or wing. Not all NDE technologies investigated in the research described in Section 3.1.1 will be directly applicable to large area inspection. Therefore it will be necessary to evaluate and downselect specific NDE tools that can then be further developed into large area systems. Evaluation of NDE techniques are typically accomplished by probability of detection (POD) studies on a statistically significant set of representative flaws. Additionally as emerging methods show effectiveness, these can be evaluated for rapid, large area application. Once the selection of candidate technologies has occurred, miniaturization efforts can begin. This will require the development of small sensors and systems, which utilize the methodologies described in Section 3.1.1, that can be easily transported over large areas. Doing this will facilitate rapid inspection that can be achieved without compromising flaw resolution.

NDE implementation at the repair depot level, to manage the structural health of large aircraft, will require the integration of data from different sensors, NDE techniques and physics-based models. These orthogonal systems, developed at a coupon level as described in Section 3.1.1, must be expanded and integrated to provide a complete picture of the health of an aircraft structure or engine. This integration must include the ability to collect, process, interrogate, store and display large quantities of data in a rapid fashion. Thus considerable effort will be applied to developing efficient, robust, high-fidelity, processing algorithms for data reduction. These allow the detection and quantification of defects in materials in the presence of such things as multiple layers of paint, or field repairs that have the potential to negatively impact some inspection technology. Ultimately, this integration will result in validated, prototype NDE systems that can be demonstrated on large aircraft structures.

Additionally, to effectively characterize engine components will require sensors and instrumentation able to withstand high temperatures. To accomplish this goal, it is necessary to develop laboratory and application grade high temperature thin- film bulk and nanostructured sensors applicable at surface temperatures up to 1100^{o}C and under high gas flow and pressure conditions. The emphasis will be on thin-film rather than wire sensors because thin film sensors are superior to conventional wire sensors in a variety of ways. They are more accurate because they are in direct contact with the surface substrate. They are lighter and require no surface machining, so they do not change the thermal or structural properties of the substrate upon which they are mounted, and their low profile ensures minimal disturbance to gas flow over the surface.

3.2.2 Structural Integrity (2.2)

The safe operation of a transport aircraft depends on the design having adequate structural integrity and residual strength in the event of an in-service failure or damage event. Prediction of damage initiation, damage propagation and overall residual strength for damaged structural components subjected to complex loading is important in assessing aging aircraft, and in designing of future aircraft where unitized structure (e.g., integrally stiffened structure) or new material systems are being employed.

<u>Fuselage and Wing Structure</u>   Damage initiation and damage propagation in aircraft structure and structural residual strength are effected by local damage conditions at structural detail features, the interaction of structural elements and subcomponents, and the changes in internal load path distributions as damage propagates. Determining the structural integrity and residual strength of an aircraft structure with damage requires a nonlinear analysis capability that accounts for material and geometric nonlinearities, and accurately represents crack growth or damage progression in built-up structures. This capability will be developed by integrating high-fidelity geometrically nonlinear global models that account accurately for local deformation effects and structural element interactions with the material nonlinear damage models developed at Level 1. The models will be further extended by incorporating decohesion elements, developed in previous programs, to capture delamination failures and the interaction between propagating damage and local detail features. In addition, modeling and analysis strategies will be developed for representing the relationships, developed at Level 1, between aging related degradation and material behavior in the structural integrity analysis.

Experimental studies of as-manufactured and aged structural elements and built-up structural panels subjected to representative loading will be conducted to identify critical failure characteristics and to validate the structural analysis methods. In addition, parametric studies will be conducted using the validated models to assess the effects of material and structural parameters on structural integrity. Results of these studies, coupled with the increased fundamental understanding of damage processes and failure mechanisms developed at Level 1, will guide the Level 3 development of design oriented analysis tools, and advanced material systems and damage containment concepts for improved structural integrity.

<u>Aircraft Engine Fan Containment Cases</u>   Jet engine blade-off events are a critical safety issue and extremely difficult to predict, resulting in highly conservative design/development practices and engine fan containment case structures with safety margins that are not well quantified. Understanding the myriad effects of aging mechanism, composite material architecture, and structural configuration on impact resistance and damage tolerance of containment structure is key to optimizing containment structure safety and efficiency. The immediate impulsive loads generated by the failed blade impacting the case and the subsequent cyclic loads propagated through the engine static structure into the airplane wing structure due to the unbalanced turbo machinery rotor dynamic interactions must also be considered in assessing aircraft structural integrity in a blade-off scenario.

Simulation of the more local blade-case impact mechanics as well as the more global engine-airframe structural system dynamics requires development of multi-fidelity structural analysis tools for predicting overall structural response and structural integrity. This capability will be developed by integrating models developed at Level 1 to represent strain-rate dependent material behavior including the effects of aging degradation on material properties, with models developed at Level 2 to represent unbalanced turbo machinery rotor dynamic interactions. The computational framework to provide a coupled propulsion system-airframe system structural analysis capability will be achieved by implementing the new Level 1 and 2 models into the LS-DYNA and MSC.NASTRAN commercial software tools. Ballistic impact tests and post-impact structural loading tests will be conducted on as-manufactured and aged subcomponents (flat and cylindrical panels) as well as full-scale prototype containment case structures to validate the new models and analysis capabilities.

3.2.3 Lifing Methods and Material Durability (2.3)

The ability to accurately predict the remaining life of components for an operational aircraft is of paramount importance to ensure safety and reliability for both commercial and military applications. The higher stresses, temperatures and aggressive environments to which today's airframes and propulsion systems are subjected make it imperative that accurate and robust life prediction methodologies be developed to track the evolution of damage and provide accurate assessments of the component reliabilities throughout the life of the aircraft.

Metallic Materials Fatigue life prediction methodologies for metallic structure have evolved from strictly empirical approaches based on applied uniaxial stress range and mean stress to high-fidelity approaches in which the failure process is divided into its subcomponents and modeled in detail. Thus the fatigue crack initiation and fatigue crack propagation stages are modeled separately, load interaction effects are considered, the effect of the environment is taken into account, and other important factors such as multiaxial loading are incorporated. For high temperature propulsion components, such factors as high temperature creep-fatigue interactions and other environmental phenomena such as oxidation also contribute to damage accumulation and must be integrated into the fatigue life prediction methodology.

Life prediction models for aging metallic aircraft still require extensive development to capture some of the failure modes that occur in components that have been in service for extended time. For example, the effect of pre-existing corrosion on the initiation and propagation of small cracks in airframe and propulsion components, stress corrosion cracking, corrosion fatigue, oxidation damage and changes in surface enhancement induced residual stresses are not well understood and thus are not captured in the current generation of life prediction models. Another area where the life prediction methodology needs further development is high temperature crack growth with long dwells. Under these types of conditions, linear-elastic-fracture-mechanics-based crack driving force parameters used in current models may be inadequate to describe the stress redistribution near the crack tip. The visco-plastic crack driving force parameters and the incorporation of atomistic modeling, to capture these effects, are still in the early stages of development. It has also been shown that the current load interaction models are not capable of accurately predicting the overload effects which occur at high temperatures and long dwell times.

Various strategies for multi-scale modeling can be considered, including: casting the results of MD analyses as constitutive relations in micromechanics analyses, direct hybrid (MD-FE) simulation models, coupling methods, quasicontinuum methods and equivalent continuum mechanics methods. The goals of each of these multiscale modeling methods are similar: to emphasize the advantages of each of the component methods (e.g., accuracy of MD at small scales, computational efficiency of FE at larger scales) and to downplay their respective disadvantages (e.g., small domain for MD and empirical constitutive relationships for FE). Taken as a whole, the multiscale modeling methodologies are very generic and can be used for any interface subject to fracture, as long as its atomistic content and structure are known. Due to the variety of novel methods that have been considered to embed atomistic models within a continuum based matrix, it would be highly advantageous to partner with additional researchers through the NRA to share information and work on parallel efforts.

Composite Materials   Life prediction methods for composite structures are currently largely empirical. The economic life and safety of composite material systems is often determined by the rate of accumulation of defects, damage and environmentally induced changes in material properties. This accumulation of damage can lead to irreversible changes in a several engineering properties including stiffness, strength and fracture toughness. There is currently considerable uncertainty in the prediction of the changes in PMC properties as they are exposed over their lifetime to complex stress, moisture and temperature conditions. The inability to predict the long-term performance of PMCs is due to an inadequate understanding of the underlying physical mechanisms for material degradation, damage accumulation and failure in the highly heterogeneous and anisotropic material structure.

A multi-disciplinary team with experience in polymer chemistry and physics, materials, mechanics and experimental mechanics will be employed to develop an integrated multi-scale modeling capability to relate characterization of materials aging responses to structural performance. Atomistic and computational chemistry models consistent with critical degradation mechanisms identified in Section 3.1.4, "Material Science," will be developed to characterize and relate polymer and fiber/matrix interface degradation mechanisms to changes in material behavior. These relationships must be understood before developing methodologies to predict long-term performance of composite structures.

Summary   While significant progress has been made over the years in improving the fidelity of fatigue life prediction models, considerable work is still required to further develop the methodology, especially for failure modes associated with aging aircraft related problems. This program will focus on some of these issues in order to improve the predictive capability of the models.

For each of these classes of material, fundamental strategies for computational damage science must be developed that are specific to the materials and the fracture/deformation process considered. For example, because of the dominant length scales involved, much can be learned about the deformation mechanisms of nanocrystalline aluminum through the use of MD simulations alone. However, since one billion atoms of aluminum occupies a volume of only about $6x10^{-20}$ m^3 and represents the limit of current computational resources, it is obvious that robust multi-scale modeling strategies are required to explore dominant fracture mechanisms at all but the smallest length scales.

3.2.4 Mitigation Technologies (2.4)

In order for new materials to mitigate aircraft aging in practice, their contribution will have to be validated through advanced analysis, test and certification. In addition, designers need to know the impact of advanced materials, sensors, and NDE methods and how to optimize a system that includes them. Furthermore, the effects of new technologies on downstream operations, logistics and maintenance have to be introduced into the design process as early as possible.

Adhesive Bonds   Delamination analysis methods pioneered at Level 1 will be extended to mixed-mode cases and validated for more complex composite architectures (e.g. fiber pre-forms) and component geometries. In another task, new adhesives and hybrid composite compositions will be formulated and previously validated accelerated aging methods will be applied to confirm understanding (derived from physics-based models) of the effect of resin chemistry on degradation mechanisms.

Wiring We plan to design a prototype next-generation cabling system/harness. This multiplexed distributed wiring will contain embedded sensors to detect over/under voltage/current (shorts/open circuits), temperature, etc. That information will be used to reroute a damaged line to a non-damaged path, providing mitigation on-the-fly. The data would also be stored for download. A working prototype will be constructed using current surface mount technologies and the design will be continually improved upon as technology advances.

Advanced Composites for Aircraft Engine Fan Containment Cases The most promising candidate(s) of the fiber pre-form based composites investigated under Level 1 will be selected for scale-up demonstration of prototype engine fan containment case structures in both as-manufactured and aged conditions. Prototype testing could include component level ballistic impact and post-impact structural integrity (damage tolerance) tests conducted at NASA GRC facilities, and perhaps sub-system level (fan rig) or system-level (engine stand) blade-off tests conducted in collaboration with engine industry partner(s). NDE for material quality assurance, damage assessment during testing, and damage model refinement will be employed to better characterize effects of aging.

Powder Metallurgy Superalloys for Aircraft Engine Disks The alloy and heat treatment combination that provided the optimal long-term notch fatigue strength at Level 1 will be selected for scale-up demonstration. A prototype engine disk structure will be manufactured with representative rim attachment geometry to simulate the loading in a real disk; data derived from the notched fatigue specimens conducted under Level 1 and finite element analysis will be employed to predict the performance of the prototype. A spin rig fatigue test will verify the notched fatigue strength of the selected alloy/heat treatment combination.

Function-based Architecture Design Traditionally, failure modes are examined during later stages of design, and are highly dependent on the experience of the designer. In this task, functional models of major components and systems will be built based on a functional taxonomy that is comprehensive and repeatable. Databases on historical failures and on potential failures from FMEAs and expert elicitation will be combined to produce component-to-failure mappings. When designers are aware of past and potential failure modes, functional models can be changed to avoid these failures.

Design for Maintainability A first step toward design for maintainability is to identify maintainability risks. In some cases, existing data sources can be leveraged (including military, manufacturers and operators), but where specific and current data is lacking, systematic approaches to surveying and observing maintenance and inspection activities may be required. Next, existing human reliability and risk assessment tools will be applied to evaluate usability of new mitigation strategies being planned in the AADP. Finally, risk-based tools for optimizing human and system reliability can be introduced.

3.3 Level 3 – Multi-Discipline Capabilities

3.3.1 Detect (3.1)

To effectively develop system-level detection capability it is necessary to establish a linkage between structural integrity research and NDE/SHM systems (Sections 3.2.2 and 3.2.1). This would require that the life-prediction methodologies using refined physics-based models for metallic and composite airframe structure, propulsion components and electrical systems be capable of integrating the flaw characterization results obtained by depot-level NDE systems.

Additionally, the NDE techniques must be flexible enough to allow inputs from the life-prediction methodologies to affect the inspection areas and the level of detail obtained so that the characterizations are useful. Another important aspect of developing successful detection capability is to be able to quantify the damage and environment state for full-scale test articles. For example, to be able to accurately predict when a metallic joint may fail it is important to understand not only what damage, but what environment the joint may have seen that is causing degradation that may lead to shortened life of the joint. Doing this will include integrating information available from any IVHM sensors and from ground based inspection systems designed to determine environmental state. These results can be inputs to the life-predication methodologies allowing determination of remaining life.

Finally, to effectively manage damage and degradation inspection technology must be developed that can be used not only to find damage in original materials, but also to assess the quality of repairs performed to correct damaged regions. This involves understanding how the repair materials, geometries and techniques affect the NDE technologies and demonstrating the ability to inspect both metallic and composite repairs.

3.3.2 Predict (3.2)

Traditional predictive tools for life and strength assessment are based on fracture mechanics methods that are more than fifteen years old. These analyses lack capability for the prediction of crack propagation in anisotropic materials such as highly textured metallic and composites materials. This limitation is further exacerbated for integral or built-up structures where a propagating crack is affected by multiaxial loads and the geometry of the structure dictates that a crack may not grow along a single direction and the crack front can be highly irregular in shape. Additionally, the influences of aging processes on the life of a component are generally treated very empirically and can only be assessed for a particular exposure condition that has been simulated. Consequently, this project is looking to develop an integrated predictive methodology by developing multiscale life and strength predictive tools by integrating atomistic-based models with continuum models, developing three-dimensional continuum models, and the application of failure criteria in continuum models for the combined effects of load and environment.

To develop robust predictive capabilities, it is critical to establish connectivity with the detection and design tools that are detailed in Sections 3.2.1 and 3.2.4 and 3.3.3. Communication between these technologies will make it possible to understand the resolution of flaw detection for the materials systems of interest and the required outputs from the predictive tools to allow for the development of design tools for the development of next generation materials and the design of integral and built-up structure.

3.3.3 Mitigate (3.3)

At this level, material design tools will be applied to aid system integration; for example to evaluate durability of multifunctional materials or environmental effects on sensors.

To evaluate the system-level effects of planned mitigation strategies, we will need to assess current methods for incorporating mitigation technologies in design and evaluate the influence of new materials on total system reliability and maintainability. We plan to develop tools with which a team of engineers/designers can make decisions and exchange information about their decisions and estimates of design parameters, along with the uncertainty and risk associated with the decisions. Specifically, the methods developed here will enable uncertainty to be added for each parameter estimate during a collaborative design trade study, and enable designers to reallocate resources based on risk due to functional failures. Using an automated system analysis and optimization process we will optimize a system architecture that includes new materials and sensors.

For aging aircraft, proper maintenance and inspection methods can significantly help with the timely and accurate detection of aging related hazards. A major roadblock to this is when designers do not know what maintainability functions and issues to consider. Designing for maintainability from the beginning of the design process is the best way to capture this functionality and associated requirements. Models of maintainability risks associated with specific inspection and operational conditions will be developed using empirical data and probabilistic modeling techniques and will be applied to compare the effectiveness of mitigation technologies and processes delivered by the AADP.

3.4 Level 4 System Level Validations

3.4.1 Experimental Validation of Airframe, Propulsion and Flight System Durability

Level 4 of the AADP aims to integrate and apply at a system-level, detect, predict, and mitigate technologies in order to understand the functional interactions among themes and maximize the impact of integrated solutions. The tasks defined in this research area bring in end-user procedures and decision processes that characterize operational-level risks and practices. These considerations feed system-level analysis of the cost and risk associated with aging and point to the critical factors that are most detrimental to system-level operations. Analysis of these critical factors is used to define strategies and requirements for specific technology developments at the lower levels in the project. In addition to analysis conducted within the project, annual inter-agency and intra-agency portfolio assessments will be conducted. At these meetings, technical progress to date, plus system-level data on emerging end-user issues and concerns, will be considered and the project portfolio will be adjusted as necessary.

Early in the project, an integration framework will be assembled that collects and relates detect, predict, and mitigate capabilities. The framework will apply current state-of-the-art capabilities in each theme to establish a baseline system-level capability using data from historical user/operator databases. The integration framework may be augmented as additional considerations pertaining to operational-level and system-level risks and benefits are identified throughout the project. After the second and fourth year of the project, advanced technology methods will be inserted into the integration framework, and system-level capabilities will be reassessed. The increasingly integrated risk model that evolves will point to optimized solutions and opportunities to experimentally validate specific combinations of detect, predict, and mitigate solutions. At the end of the fifth year, the project will conduct system-level experiments to validate integrated methods for the detection, prediction, and mitigation of aging-related hazards. The validation will focus on an aircraft system and will include detect, predict and mitigate strategies applied as an integrated solution. The Challenge Problems represent a set of diverse applications, each with research tasks defined in some, or all, of the three theme areas. The collection of research tasks from the project's Challenge Problems spans several aircraft systems and connect across the detect, predict, and mitigate themes to create operationally valid opportunities to conduct system-level experiments.