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AIR VEHICLE INTEGRATION AND TECHNOLOGY RESEARCH (AVIATR)

Delivery Order 0003: Condition-Based Maintenance Plus Structural Integrity (CBM+SI) Demonstration

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14. ABSTRACT
This report summarizes recent progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity (CBM+SI) – Basic Phase. The main objective of this task is to document the requirements for both CBM+ and the Aircraft Structural Integrity Program (ASIP) related technologies based upon the selected candidate structure. Three major Steps are used to achieve the main objective. Both, Step 1, researching and documenting ASIP technology requirements, and Step 2, researching and documenting CBM+ technology requirements have been completed and were discussed as part of the March progress report. The specific results of these steps are not presented here. The reporting on this portion of the project continues with researching and documenting the goals, objectives, requirements and business needs of CBM+SI.

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Summary of August Bi-Annual Report

This report summarizes recent progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity (CBM+SI) – Basic Phase. The organization of the report follows the Work Breakdown Structure, and specifically documents the progress during the current reporting period, April through August 2009 on the Strategy Development task (WBS 1.1.1) which contains the following key sub-sections:

1.1.1 Strategy
- 1.1.1.1 Requirements
- 1.1.1.2 Architecture Prototype
- 1.1.1.3 Data Flow
- 1.1.1.4 Beta Testing

This document provides an update to the progress on this project during the current reporting period. In the March progress report, most of the effort was focused on sub-section Requirements (1.1.1.1). Through the current reporting period, sub-sections 1.1.1.1 and 1.1.1.2 have been completed and sub-sections 1.1.1.3 and 1.1.1.4 are still in work. For those items completed and documented in the March progress report, for example, the Steps 1 and 2 of sub-section 1.1.1.1, these items will not be reiterated in this report. For those incomplete sub-sections, a brief summary of the task objective and plan for each of the remaining tasks will be presented and discussed.

In the Requirements sub-section (1.1.1.1), the technology requirements for all the identified CBM+SI technologies (Step 3) needed to demonstrate the CBM+SI benefits on the demonstration example have been developed and summarized.

In the Architecture sub-section (1.1.1.2), the current ASIP engineering analysis process and the analysis process for the CBM+ 10 enabling technologies and concepts are studied and summarized. A CBM+SI architecture prototype for the selected demonstration example has been developed and summarized. With the proposed CBM+SI architecture, a compliance matrix has been developed to make sure that the proposed architecture meets the following key criteria:

1. Integrated individual tracking data with Integrated Vehicle Health Management/Structural Health Management (IVHM/SHM) data,
2. Diagnostic and prognostic capabilities,
3. Enhanced maintenance quality,
4. Information tools, and
5. Total Life Cycle Systems Management (TLCSM).

In the Data Flow sub-section (1.1.1.3), the current ASIP reliability and risk assessment data flow used to determine the maintenance schedule based on the MIL-STD-1530C has been studied and summarized. The same risk assessment data flow will play a major role for the proposed CBM+SI architecture which will be completed by the end of September.

In the Beta Testing sub-section (1.1.1.4), a beta testing plan was developed based on the proposed CBM+SI architecture prototype (sub-section 1.1.1.2) to demonstrate CBM+SI benefits on the selected structural component using the proposed Technical Performance Measurement (TPM) analysis. To perform the comparison, the proposed beta testing plan defined the baseline case and three other testing cases with consideration of various risk assessment strategies and Structural Health Monitoring (SHm) technologies. All of these testing cases will be demonstrated during the second phase of this project and a compliance matrix (as discussed in sub-section 1.1.1.2) will be produced to make sure these cases have met all the key CBM+SI technology criteria. However, to fully implement all the proposed CBM+SI technologies and concepts, there are some technology shortcomings and gaps which can be identified, for example, a high-fidelity SHm capability. These shortcomings and technology gaps will be identified and summarized.

The Strategy Development phase is planned to be completed at the end of September. We are on schedule to meet this date and start the Demonstration phase of the program the beginning of October. At the present time, there are no major issues to report. The project is expected to be completed on schedule and on budget.

1.1.1 Strategy

1.1.1.1 Requirements

The main objective of this task is to document the requirements for both CBM+ and the Aircraft Structural Integrity Program (ASIP) related technologies based upon the selected candidate structure. Three major Steps are used to achieve the main objective. Both, Step 1, researching and documenting ASIP technology requirements, and Step 2, researching and documenting CBM+ technology requirements have been completed and were discussed as part of the March progress report. The specific results of these steps are not presented here; the reader is encouraged to refer to the March progress report for information relating to this previously completed work. The reporting on this portion of the project continues with Step 3, researching and documenting the goals, objectives, requirements and business needs of CBM+SI. The reader should note that some study results which were previously presented in the March progress report are reiterated for the completeness of the report.

A CBM+SI Continuous Process Improvement (CPI) process to continuously update the technology needs which have been defined. While a majority of the Strategy Development has been completed at this point, some work still remains through the end of the planned development period, with this in mind as this work is closed out through the end of September, new requirements may become apparent and they will be incorporated accordingly. To give visibility to this CPI improvement, the current requirement task will not be closed out until the Strategy Development is completed at the end of September. In the March progress report, an update on a special effort to compare two F-15 structural components using three key criteria (TPM data requirement, F-15 data availability, and SHm suitability) was presented. This effort was still in work at the time of the March progress report. This effort is now complete and a final decision was made to move forward with the "Frame Station 626 Lower Bulkhead Flange at the Inboard Longeron" as our demonstration structural component. Many of the requirements were tailored based on this structural component in mind.

Step 3. Study and document CBM+SI goals and objectives, study and document CBM+SI business needs, study and document requirements for the CBM+SI technologies required to demonstrate the CBM+SI benefits on the selected structural component

For the CBM+SI goals and objective, the team first summarized key CBM+SI goals and objectives keeping in mind for CBM+SI approach to achieve level 4 of the U.S. Air Force CBM+SI pyramid. These goals and objectives will be used to guide the team in developing the most appropriate CBM+SI strategy. For the CBM+SI business needs, the team integrated both ASIP needs (Step 1) and CBM+ (Step 2) to form a general CBM+SI business needs. To satisfy both the goals and objectives and the business needs, the team identified the CBM+SI technologies required to demonstrate the benefit CBM+SI as applied to the selected structural component. The requirements for these identified technologies including SHM technology have been defined. Again, following our continuous improvement model, the task will not be closed out until the Strategy Development is completed at the end of September.

CBM+SI Goals and Objectives

The objective of the baseline task is to develop and demonstrate a CBM+SI strategy for at least one structural application on a USAF weapons platform. Again, most of the text below was a

part of the proposal and is included here for completeness of the discussion. As part of this demonstration, the benefits to the Air Force as result of employing this CBM+SI strategy shall be determined in terms of:

- Total cost of ownership
- Aircraft availability rates
- Maintenance hours per flight hour

Develop and demonstrate CBM+SI Strategies for structural Applications on a USAF weapon platform to include:

- Developing integrated, predictive maintenance approaches, which minimize unscheduled repairs, eliminate unnecessary maintenance, and employ the most cost-effective maintenance health management approaches.
- Determining an optimum mix of maintenance technologies.
- Identifying the optimum opportunity to perform required maintenance.
- Providing real-time maintenance information and accurate technical data to technicians and logisticians.

In addition, the developed CBM+SI must be able to achieve the level 4 of the CBM+ pyramid as shown in the Figure 1 below. It is important to recognize the requirement in order to identify required CBM+SI technologies to demonstrate this level of benefit on the selected structural component.

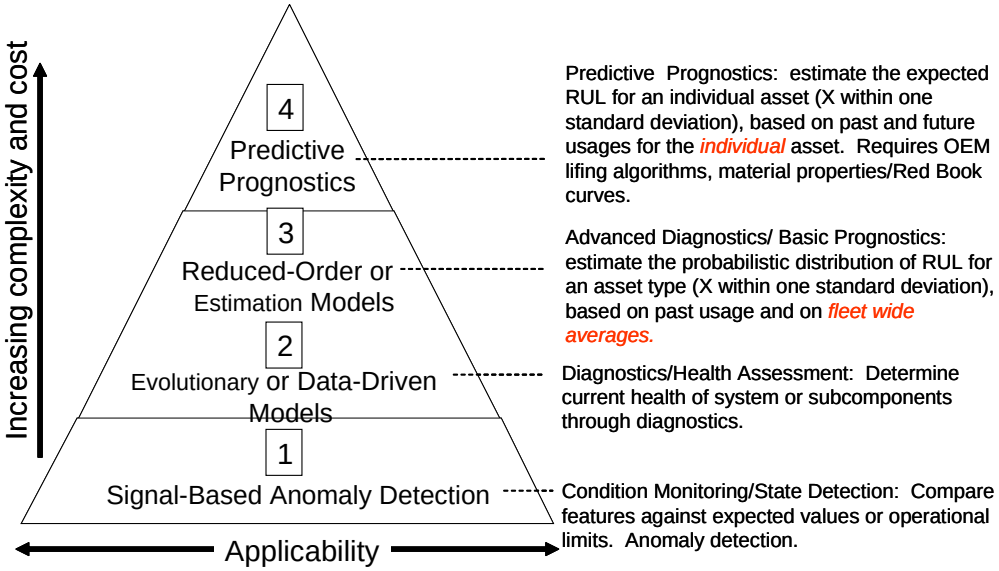

Figure 1. CBM+SI Pyramid chart

CBM+SI Business Needs

CBM+SI business needs are developed and summarized by considering and integrating both ASIP and CBM+ business needs as follows:

1. For the initial Basic Phase of this contract, the following CBM+SI business needs will be considered and demonstrated:
    a. ASIP side: Improved risk and reliability methods for sustainment related issues (service life extension programs, potential for missing damage during inspections,

and unanticipated air vehicle damage). ASIP community support to ensure structural safety record is at least preserved, if not improved, as USAF fleet continues to age.

   b. CBM+ side: Need to predict equipment failures, need for a holistic view of equipment condition, need for greater accuracy in failure prediction, need to reduce the cost of ownership, need to improve equipment and component reliability, need to reduce equipment mean down time (logistics responsiveness), and need to optimize equipment performance.

2. For the option phase of this contract, only one business needs from the ASIP side remains to be addressed.
   a. The means to determine air vehicle risk and reliability for changes from legacy approaches during development.
   b. This business needs will be considered in only a very limited sense during the forward looking assessment sub-section of the Demonstration phase.

Identify Technology Needs to Meet CBM+SI Business Needs

To meet all of the business needs mentioned above, as well as the goals and objectives defined earlier, the team identified technologies that need to be incorporated into a comprehensive CBM+SI strategy. For the basic phase of this contract, the main objective is to provide a business case assessment of the application of the developed CBM+SI Strategy on the selected structural component. Therefore, for the Requirements development, we will focus on the technologies needed for the selected structural component.

1. ASIP risk assessment capability
   a. MIL-STD-1530C
   b. Additional requirements for risk assessment. For example, how do the requirements change in performing the risk assessment in the presence of SHM data?
2. Prognostic
   a. Structural Health Monitoring (SHm)
   b. ASIP risk assessment process
3. Diagnostic
   a. ASIP: Individual Aircraft Tracking (IAT), Loads/Environment Spectra Survey (L/ESS), Forced Structural Maintenance Plan (FSMP)
4. Information tool – Portable Maintenance Aid, Interactive Electronic Technical Manuals
5. Advanced NDI
6. Reliability Centered Maintenance
7. Joint Total Asset Visibility: Technical Performance Measurement (TPM)

Notice that CBM+ is a Continuous Process Improvement (CPI) strategy so is CBM+SI. Under CPI principle, it is envisioned that the elements of CBM+SI should be revisited as the life cycle progresses, conditions change, and technologies advance. The developed CBM+SI strategy includes fully developed technologies and processes that can be implemented now as well as yet-to-be developed capabilities. CBM+SI also use proof-of-concept and prototype activities that can be applied incrementally, not waiting for a single solution package. To maintain consistency, CBM+SI development should be based on a broad architecture and an enterprise framework that is open to modification and can be easily adjusted.

In order to develop a CBM+SI strategy which meets the defined business needs for the selected historical ASIP application, the team will consider the following basic steps, which is taken from the CBM+ guidebook [11]:

1. Understand that CBM+SI strategy is a continuous improvement initiative over the life cycle of a weapon system or equipment.
2. Ensure full understanding of the planning, implementation and operations phases of CBM+SI by the implementation team, functional managers, stakeholders and customers.
3. Initiate the CBM+SI planning phase and complete the processes needed to develop the CBM+SI strategy and to begin the selection of applicable technologies.
4. Build on planning phase actions by managing the implementation phase as a time-phased execution of process changes, technology insertion, organizational realignments, and equipment changes.
    a. Although, this step here is more closely related to the option phase of this task order program, it may be briefly addressed in the forward looking step of the Demonstration task.
5. In the operations phase, incrementally deploy CBM+SI capabilities to operational user locations and continue through full execution of required CBM+SI capabilities.
6. Continuously assess CBM+SI progress and overcome barriers to successful execution as they occur.
7. Discontinue or modify CBM+SI capabilities for specific weapon systems and equipment as requirements evolve with the cessation of use or replacement of those capabilities.

The above CBM+SI CPI process is discussed in detail in Appendix A.

CBM+SI Requirements for the Selected Structural Component

For the selected structural component, by applying developed CBM+SI planning phase process, it is envisioned that the key technologies, referenced above, must be applied in order to achieve the CBM+SI goals & objectives, and demonstrate a benefit. The requirements for these identified key technologies have been documented in Appendix B except SHM, which is documented in Appendix C.

Additional Requirement Task: Down-Select the F-15 Structural Components

In order to compare the two F-15 structural components, the team developed three key criteria (TPM data requirement, F-15 data availability, and SHM suitability) to down-select the structural component that will be able to demonstrate the most benefits by using the developed CBM+SI strategy. The results from this effort also supported this requirements task by providing TPM data requirements and its relationship to TLCSM, the F-15 data availability and its current CBM+ technology usage status, and SHM capability assessment for the selected structural component. These three key criteria are shown as follows,

- *What are the data requirements for the Technical Performance Measurement (TPM) analysis?* TPMs will be used to develop a comprehensive CBM+SI strategy. A report on TPM data requirements has been completed and presented in Appendix D.
- *Can the F-15 program provide all the necessary data for TPM analysis for the two structural components under consideration?* A detailed report on the assessment of data availability is included in Appendix E. In March, there are a few data categories which are outstanding, after a thorough study and consultation with Warner-Robins, it was

confirmed that information on the availability of mission profile, maintenance, equipment, and labor costs data are available for both selected locations.

- *Are both components suitable to apply currently available advanced SHM technology?* The application of SHM technology will be necessary to demonstrate a compelling benefit of CBM+SI; therefore, it is critical to determine which SHM technologies will be suitable for the each of the two structural components. A report on the suitability and capability of the currently available SHM technology on the two F-15 structural components has been completed and presented in Appendix F.

From the above three criteria, the F-15 structural component "Frame Station 626 Lower Bulkhead Flange at the Inboard Longeron" was selected to demonstrate the benefits of CBM+SI. In the subsequent sections of this project, the selected structural component will be evaluated using the developed CBM+SI architecture prototype and its associated reliability and risk assessment strategy to perform a feasibility study with several maintenance approach options. The most cost effective maintenance option will finally be selected.

1.1.1.2 Architecture Prototype

The main objective of this task is to develop an integrated, predictive maintenance CBM+SI architecture prototype for an identified F-15 platform structural component. Four major Steps are required to achieve this objective. The development work has been completed and presented in detail in the specific appendices listed below. However, as the remaining elements of the Strategy Development task are completed, minor changes to the Architecture Prototype may be required. Any necessary changes will be completed by the end of September.

Step 1. Evaluate Current ASIP Engineering Analysis Process

The planned effort in this step was to study and document the current ASIP engineering analysis process with special attention to any established risk assessment process. The detailed results of this Step are presented in Appendix G.

Step 2. Evaluate Analysis Process for the CBM+ 10 Enabling Technologies and Concepts

The planned effort in Step 2 was to study and document the CBM+ analysis process especially the 10 most important technologies and concepts. Compare with ASIP engineering process and identify similarity and difference for developing of a CBM+SI engineering analysis process especially the risk assessment data requirements. The detailed findings and results are summarized in Appendix H.

Step 3. Develop a Preliminary CBM+SI Architecture Prototype for the selected demonstration example

The planned effort in Step 3 was to develop a preliminary Architecture Prototype for the selected demonstration example based on identified ASIP and CBM+ analysis processes from Steps 1 and 2 and to identify technologies required to implement the Architecture Prototype. The developed Architecture Prototype is presented in Appendix I.

Step 4. Develop a Compliance Matrix for the Proposed CBM+SI Architecture and finalize CBM+SI Architecture Prototype

The planned effort in this final step was to develop a compliance matrix based on the developed CBM+SI Architecture Prototype from Step 3 to determine if all the key CBM+SI elements have been considered and included, e.g., integrated individual tracking data with IVHM/SHM data,

diagnostic and prognostic capabilities, enhanced maintenance quality, information tools, and Total Life Cycle Systems Management (TLCSM). The results of this Step are presented in Appendix I.

1.1.1.3 Data Flow

The main objective of this task is to define the data flow of the developed architecture prototype. All the data shall be collected and stored within the historical database for further decision making cycles and future designs. To implement the task, ASIP reliability and risk assessment data flow and data requirement will be studied first and used as a reference for CBM+SI reliability and risk assessment data flow.

Step 1. Study current ASIP reliability and risk assessment data flow and its data requirements

This effort was started in August, the current findings and results are presented in Appendix J. The objective of this step was to study current ASIP reliability and risk assessment process used to determine the maintenance schedule based on the MIL-STD-1530C. Study and define the data flow for the risk computational strategy based on IAT, Load Spectrum data, material data, Non-Destructive Inspection (NDI) Probability of Detection (POD), Equivalent Initial Flaw Size (EIFS), etc.

Step 2. Define CBM+SI data flow for reliability and risk assessment

Planned effort: Study and define the CBM+SI data flow for reliability and risk assessment based on the ASIP's data flow (from Step 1) with consideration of SHM data impact, advanced NDI data impact, information tools data impact, and data requirement for TLCSM. From the above, define an updated risk computation strategy with consideration of additional SHm sensor data, advanced NDI, information tools, and others.

This Step has been initiated in August and will be completed in September.

1.1.1.4 Beta Testing

The main objective of this task is to develop a beta testing plan based on the developed CBM+SI architecture prototype to demonstrate CBM+SI benefits on the selected structural component. From the down-select process, feasibility of CBM+SI process has already been studied and shall be implemented accordingly based on the developed CBM+SI architecture prototype. In addition, technology shortcomings and gaps needed for a successful demonstration will be identified. Two Steps are developed to meet the objective.

Step 1. Based on the selected structural component, apply the proposed CBM+SI architecture prototype and its reliability and risk assessment strategy to perform a feasibility study for several maintenance options and select the most cost effective maintenance optimization.

Planned efforts: Perform a feasibility study by considering the following maintenance options:

- Baseline (deterministic)
- Baseline (risk based)
- SHm on board or off-board data extraction
- SHm with advanced NDI checkup or not?

- SHm with advanced NDI and additional Interactive Electronic Technical Manuals (IETM) development

All the findings for this Step are summarized in Appendix K.

Step 2. From Step 1 results, identify CBM+SI technology shortcomings and gaps needed to be resolved for a successful CBM+SI technology demonstration.
Planned efforts: Based on the results from the feasibility study in Step 1, identify technology shortcoming or gaps that are needed to perform a successful CBM+SI technology demonstration. Some technology gaps identified:

- Robust embedded sensors (SHm)
- High fidelity data reasoners (SHm)
- SHM real-time data acquisition and fusion techniques
- Risk assessment with SHM data, PMA data, Advanced NDI POD data
- TLCSM data accuracy and source (Availability, Cost, and Maintenance Hours per Flight Hour)

This Step has been initiated in August and to be completed in September.

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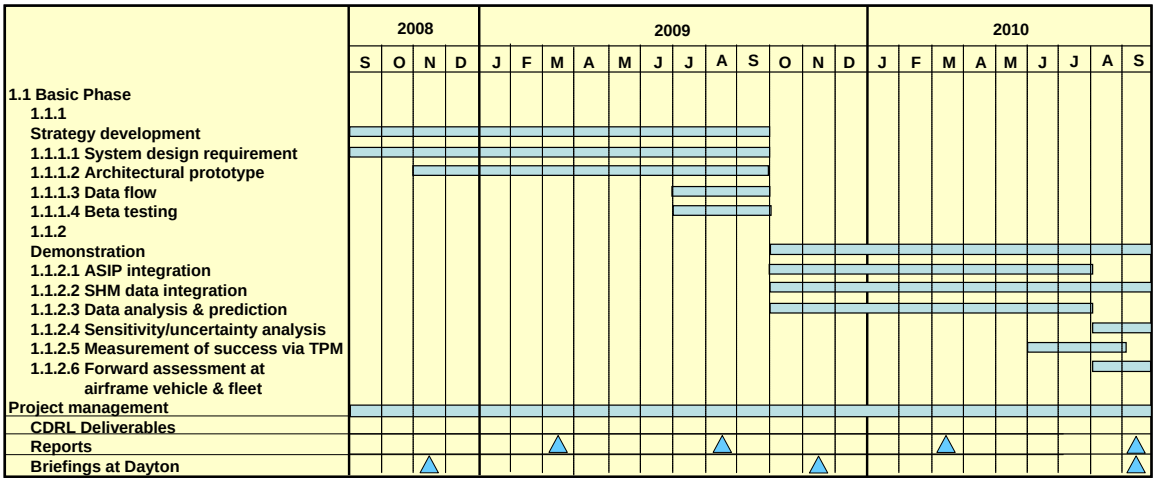
Schedule



Appendix A. CBM+SI CPI Process Development

CBM+ and CBM+SI are both considered a Continuous Process Improvement (CPI) strategy. Under CPI principle, it is envisioned that the elements of CBM+SI should be revisited as the life cycle progresses, conditions change, and technologies advance. The developed CBM+SI include fully developed technologies and processes that can be implemented now as well as yet-to-be developed capabilities. CBM+SI also uses proof-of-concept and prototype activities that can be applied incrementally, not waiting for a single solution package. To maintain consistency, CBM+SI development should be based on a broad architecture and an enterprise framework that is open to modification and can be easily adjusted. To implement a CBM+SI for a general ASIP application and our case specifically for our chosen structural demonstration article, the F-15 FS 626 bulkhead, the following basic steps for planning, implementing, and operating a CBM+SI initiative, or project, are recommended (reference to CBM+ guidebook) especially when we are trying to implement a comprehensive CBM+SI framework for the airframe of a USAF platform:

1. Understand that CBM+SI is a continuous improvement initiative over the life cycle of a weapon system or equipment.
2. Ensure full understanding of the planning, implementation and operations phases of CBM+SI by the implementation team, functional managers, stakeholders and customers.
3. Initiate the CBM+SI planning phase and complete the processes needed to develop your CBM+SI strategy and to begin the selection of applicable technologies.
    a. The step here is very similar to the basic phase of this AVIATR program. The CBM+SI team must identify the most appropriate structural component to demonstrate the benefits of CBM+SI by selecting and applying the most appropriate CBM+ technologies.
4. Build on planning phase actions by managing the implementation phase as a time-phased execution of process changes, technology insertion, organizational realignments, and equipment changes.
    a. The step here is very similar to the option phase of this program.
5. In the operations phase, incrementally deploy CBM+SI capabilities to operational user locations and continue through full execution of required CBM+SI capabilities.
    a. Widespread adoption of CBM+SI into the Aircraft Structural Integrity Programs, and a strong technical pull developed for those enabling technologies, will occur once a solid business case is made for CBM+SI.
6. Continuously assess CBM+SI progress and overcome barriers to successful execution as they occur.
7. Discontinue or modify CBM+SI capabilities for specific weapon systems and equipment as requirements evolve with the cessation of use or replacement of those capabilities.

In the following three sub-sections, the planning, implementation, and operation phases of the proposed CBM+SI CPI process will be discussed in more detail. Since the developed CBM+SI CPI process will be based on the CBM+ CPI process as defined in the Reference [11]; therefore, most of the similar parts will be referenced to the guidebook and only the sections with a different philosophy will be discussed in detail. Because the CBM+SI project baseline phase has many similarities related to the planning phase of this CBM+SI CPI process, a majority of the discussion will focus on the planning phase.

A.1 CBM+SI CPI Planning Phase

All the planning actions generally apply when an initiative is first started. For this project, it is started with an initiative to apply CBM+ onto an ASIP structural component. The key is to develop and demonstrate CBM+SI strategies for structural applications on a USAF weapon platform. Therefore, compared to a general CBM+ CPI planning process, the proposed CBM+SI CPI process does not require some of the initial effort in general, for example, familiarization with the CBM concept, ensuring that managers and employees at all levels understand CBM and are supportive of CBM objectives and planning, and developing the basic steps required to initiate the effort. The proposed CBM+SI strategy is focused on the research side and has already received management's support to apply CBM+SI strategy and to demonstrate the benefit of CBM+SI on a selected ASIP structural component. In the following, we have the following actions proposed for the planning phase:

1. Obtain Management Support
2. Perform RCM/Reliability Analysis
3. Form CBM+SI Team
4. Identify CBM+SI Target Application
5. Accomplish Proof-of-Principle
6. Prepare Implementation Plan
7. Examine New Technologies
8. Develop Data Strategy
9. Develop Architecture
10. Set Life Cycle Metrics
11. Develop Deployment/Support Strategy
12. Complete Business Case
13. Develop Resources Strategy

Details of these actions can be seen in the reference [11] and the only difference will be that the application area becomes the ASIP structural component(s). In other words, CBM+ will be modified as CBM+SI. For the developed CBM+SI strategy during the CBM+SI project basic phase, it can be related to several planning actions (7 through 10). Therefore, only these four actions (7-10) will be discussed.

7. Examine New Technologies

The most difficult task for the CBM+SI implementation team may be to correctly match available hardware, software, and supporting technology solutions to the requirements of the future maintenance process. This task must begin with the documentation of functional requirements. In the case of CBM+SI, the functional requirement can often be stated as the objectives (as listed in Section 1 of this Guidebook) and business needs (discussed in Section 3 of this Guidebook). Once these requirements are recognized and approved for a specific organization or range of equipment, a comparative analysis will ensure the operational performance or benefits of adopting CBM+SI methods and technologies can be assessed effectively.

Of course, no combination of technology is likely to provide the "perfect" solution. The team will need to make numerous compromises, trading off required capabilities against cost, time, and degree of implementation difficulty. The decision to adopt a particular technology solution should never be based solely on the merits or appeal of the technology itself. Ultimately, the advisability of acquiring a particular technical capability relies on the contribution that

acquisition makes toward improving one or more performance metrics or reducing cost factors.

Decisions on technology selection should always be made in the context of meeting functional requirements using the framework of business case alternatives. Further detail regarding applicable CBM+ technologies is contained in Attachment A.

This process of examining new technologies and defining requirements, tradeoffs, and gaps, is similar to what we have defined as our Requirements (1.1.1.1) subtask.

8. Develop Data Strategy

One of the first areas to be considered by the CBM+SI IPT should be the approach and mechanism for managing the condition and related data required to accomplish condition-based analysis whether on-, at-, or off-platform. Applying open systems or military standards will facilitate the integration of the various CBM+SI elements. It is advisable to complete the architectural interface views for data management, storage, and exchange as soon as possible. Acquiring software packages that are fully compatible with open data standards is also an essential part of a good data strategy.

The planning action described above is closely related to our Data Flow (1.1.1.2) subtask.

9. Develop Architecture

Once the CBM+SI Implementation Plan has been approved, the IPT should begin constructing the architectural views, descriptions, and profiles as prescribed by the DoD Architectural Frame-work. As discussed earlier, the CBM+SI architecture becomes a key part of the Implementation Plan particularly when defining interfaces between the components of a comprehensive condition based maintenance process. Astute managers rely on the architectural representations to identify personnel training topics, assess progress for each process component, reallocate developmental resources, integrate different process components, and explain details of the initiative to outside reviewers. When required, a system's acquisition documents should be revised to incorporate CBM+SI functionality as it is described by the architectural views. Finally, the architectural design is a validation tool that ensures the final product is complete and satisfies the needs of the customer.

Development of the framework as described above will be conducted as part of the Architecture Prototype (1.1.1.1.2) subtask.

10. Set Life Cycle Metrics

In creating the strategy for CBM+SI implementation, it is essential to identify and remain focused on strategic changes required to accomplish the transition to the desired CBM+SI environment. Lifecycle sustainment metrics provide the quantitative tools to track CBM+SI implementation and operation. As the implementation effort progresses, high-level performance and cost metrics should be developed and supporting or diagnostic metrics3 determined. Initially, however, the CBM+SI implementation team should identify which high-level metrics are required to monitor overall maintenance performance, costs, and results.

The CBM+SI implementation team should begin with metrics developed through recent research that used the "balanced scorecard" approach. A quantitative baseline that uses past experience or estimated metric targets should be developed. The balanced scorecard approach requires measures in the following areas:

- *Meeting the strategic needs of the enterprise*
- *Meeting the needs of individual customers*
- *Addressing internal business performance*
- *Addressing process improvement initiative results.*

Implementation of CBM+SI requires a structured approach to measuring both the progress of implementation and the performance and costs once the CBM process is operational.

Life cycle metrics will be determined as part of the Demonstration phase, but the basic principles will be investigated during the Beta Testing (1.1.1.4) sub task for the Strategy Development.

CBM+SI CPI Implementation Phase

Following with same philosophy as above of presenting only the sections from the Guide Book [11] which are substantively different between CBM+ and CBM+SI, for the Implementation and Operation Phases, the team does not feel there are substantive differences so the remaining process steps in these areas are provided for reference and completeness in the discussion.

1. Acquire CBM+SI capabilities (sensors, communications, data repositories)
2. Acquire Health Management software
3. Demonstrate Data Management Approach
4. Revalidate RCM/Reliability Analysis
5. Demonstrate CBM+SI element interoperability
6. Demonstrate CBM+SI Functionality
7. Complete Pilot Program Field Test
8. Resolve Performance and Cost Issues
9. Train Stakeholders and Users
10. Revise Implementation Plan
11. Update Supportability Strategy
12. Acquire Full Production Capability
13. Accomplish CBM+SI Deployment

CBM+SI CPI Operation Phase

Again, the process steps are present for the completeness of the discussion and reference; there are no substantive differences between the intention of CBM+ and CBM+SI.

1. Continuously analyze condition data at all levels.
2. Revalidate RCM/Reliability Approaches
3. Develop Performance Baselines
4. Continuously review CBM+SI metrics
5. Refresh Enabling Technologies
6. Re-Validate Human Interfaces
7. Periodically Update CBM+SI Business Case
8. Continuously Update Resources Strategy & Integrated Budget
9. Optimize Maintenance Strategies

Appendix B. CBM+SI Requirements for Demonstration Example

Requirements for the identified CBM+SI technologies are summarized below, these include, risk assessment, prognostic, diagnostic, information tools, advanced NDI, reliability center maintenance, and performance/cost measurement: The discussion is specific to the F-15 program, and the selected demonstration component FS 626 bulkhead. However, all the elements of the general assessment as discussed in the main body of the report are considered.

1. ASIP risk assessment requirements
    a. MIL-STD-1530C will be the primary requirement document for risk assessment. In addition, diagnostic task requirements are also included in this document. The key risk related task requirements will be summarized in section Appendix B.1.
    b. Additional requirements for risk assessment considered are related to CBM+ related capabilities. For example, how do the requirements change in performing the risk assessment in the presence of data from a SHm system. These changes or additions will also be included in the section Appendix B.2.
2. Prognostic
    a. Structural Health Monitoring (SHm) – This task will be summarized in the SHm requirement subtask. See Appendix C.
    b. ASIP risk assessment process (Ref., Appendix B.2, Additional ASIP Risk Assessment Requirements).
3. Diagnostic
    a. ASIP: Individual Aircraft Tracking (IAT), Loads/Environment Spectra Survey (L/ESS), Forced Structural Maintenance Plan (FSMP). This part will also be referenced to MIL-STD-1530C and will be discussed in the Appendix B.3.
4. Information tool – Portable Maintenance Aid, Interactive Electronic Technical Manuals
    a. Portable Maintenance Aids (PMAs): The F-15 has limited use of PMAs for ASIP. The platform uses laptop computers to download information, but this is limited to future transference to other equipment for diagnostics. Flight Data Recorder (FDR) information for USAF F-15's is extracted using a solid state cartridge. FDR data for current production aircraft (F-15K, F-15SG) is downloaded using an Ethernet connection to a laptop computer.
    b. Interactive Electronic Technical Manuals (IETMs): IETMS is currently in use by customers for F-15E, F-15K, and F-15SG with implementation for other versions in work. The original models, F-15 A/B/C/D work under the paper based Tech Orders. This has been a future change desired by the USAF SPO, but funding issues has prevented the update.
    c. Interactive Training: Training, in several media presentations, exists for different aspects of the F-15 inspections, diagnostics, etc., but has not been converted to an interactive format. Training has been limited to providing a straightforward concept of the steps and processes necessary to maintain and provide safety to the airframe.
5. Advanced NDI
    a. Advanced NDI – The current inspection methods for the FS626 Bulkhead are based on bolt hole Eddy Current. Warner Robins Air Logistics Center (WR-ALC) is developing an Ultrasonics based NDI method to detect cracks at the fillet

radius associated with possible crack formation. The method needs to account for multi-layered structure and sealants. WR-ALC plans to have the method documented in June 2009, so it can eventually be released for fleet wide inspections. The new procedure will be incorporated in the -36 [Reference 1].

b. [Ref. 1] T.O. 1F-15A-36, "NONDESTRUCTIVE INSPECTION USAF SERIES F-15A 73-085 AND UP, F-15B 73-108 AND UP, F-15C, F-15D AND F-15E AIRCRAFT", 1 Nov 2003, Change 4 - 1 July 2005.

6. Reliability Centered Maintenance
   a. Reliability Centered Maintenance (RCM) – RCM is discussed in the F-15 FSMP [Reference 2]. The application of RCM on the F-15 program has been established as part of the Damage Tolerance Assessment (DTA). One key element of DTA and RCM is the definition of inspection intervals for critical airframe structure. These intervals are determined using fatigue crack growth analysis and actual usage fatigue spectra. The RCM inspection worksheets are periodically updated to incorporate in-service fatigue findings.
   b. [Ref. 2] J. McFarland, "F-15 Force Structural Maintenance Plan", Boeing Report Number MDC A9236, Rev. H, 15 July 2007.
      i. Extracted from the above report: "The Reliability Centered Maintenance (RCM) analysis concept of MIL-M-5096D was subsequently established by the Department of Defense (DOD), and the F-15 System Program Office (SPO) was directed to apply the RCM technique to the F-15. This system bases the inspections on an analytical methodology for all locations determined to be fatigue critical. McDonell Aircraft was subsequently funded and given go-ahead authority on 18 January 1979 via CCP 143 to develop a F-15 RCM program for the airframe. The effort was initially scoped and planned to be accomplished by: (1) the identification and delivery of a list of Structural and Maintenance significant items, (2) the conduct of a crack growth analysis of each item on the approved significant items list, and (3) a limited test of the baseline requirements evolving from the analysis. The latter was to occur at a site to be announced. The technical data media were to be a distinctive set of Development Program Manuals (DPM). The effort was accomplished essentially as planned with one exception. A separate test and resultant DPM preparation was not accomplished. Instead existing T.O. lF-15A/C-6 Technical Orders were revised and implemented force wide. The engine analysis was accomplished by United Technologies, Pratt & Whitney Aircraft Group via CCP 051."
7. Joint Total Asset Visibility: Technical Performance Measurement (TPM)
   a. The JTAV concept is developed to improve supply/maintenance planning and responsiveness, thereby increasing operational availability, improving maintenance and logistics practices. TPM will be used to measure the benefits of the proposed CBM+SI technologies through total cost of ownership, aircraft availability, and maintenance hours per flight hour. Therefore, the application of TPM technology can also be considered or counted as a key element of JTAV.
   b. The data requirement for performing the TPM is summarized in Appendix D. In addition, the relationship between TPM and TLCSM is also discussed. Note that

the indentified data requirements were used by the F-15 program to investigate if all the required data sets were available for the two competitive structural components (see Appendix D).

B.1 ASIP Risk Assessment Requirements In MIL-STD-1530C

The risk assessment requirements were developed in compliance with ASIP Standard Mil-Std-1530C. Three major risk assessment tasks from MIL-STD-1530C are identified below and they are, Initial Risk Analysis, Certification Analysis, and Risk Analysis Updates

1. Initial Risk Analysis (MIL-STD-1530C, par. 5.2.16)
    a. An initial risk analysis shall be performed using the EIFS distribution developed under par 5.2.14.1 and par 5.3.4 and combined, when appropriate, with data from similar aircraft.
    b. A primary objective of this analysis is to demonstrate a low risk of both WFD and loss of fail-safety during the design service life when the aircraft is flown to the design loads/environment spectrum. The current version of the PROF code does not address this problem, or objective.
    c. Also, the analysis should estimate the time beyond the design service life when the risk (in terms of probability) of loss of fail-safety will become unacceptable, i.e., exceeds a previously prescribed level of acceptable risk.
    d. For non-failsafe structures, the analysis should estimate the time beyond the design service life when required safety inspections and/or modifications would result in an unacceptably high risk of aircraft unavailability and/or adverse economic consequences.
    e. Sufficient variables impacting risk shall be included in the risk analysis. Examples of such variables include, but not necessarily limited to: EIFS distribution, load spectra, chemical and thermal environment, material properties, and the NDI POD.
    f. Input:
        i. An initial risk analysis shall be performed using the EIFS distribution developed under par 5.2.14.1 and par 5.3.4 and combined, when appropriate, with data from similar aircraft.
        ii. Variables include: EIFS distribution, load spectra, chemical and thermal environment, material properties, and the NDI POD.
    g. Output:
        i. Demonstrate a low risk of both WFD and loss of fail-safety during the design service life when the aircraft is flown to the design loads from the environment spectrum.
        ii. Estimate the time beyond the design service life when the risk of loss of fail-safety will become unacceptable.
        iii. For non-failsafe structures, the analysis should estimate the time beyond the design service life when required safety inspections and/or modifications would result in an unacceptably high risk of aircraft unavailability and/or adverse economic consequences.
2. Certification Analysis (MIL-STD-1530C par. 5.4.1)
    a. Risk analysis. (par 5.4.1.1)

i. When tailoring, as described in par 1.1.2 (tailoring), has been accomplished, a risk analysis shall be performed and utilized in the initial airworthiness certification. The objective of this analysis is to determine the combined impact of all tailored ASIP tasks and/or elements on aircraft structure reliability and to verify that the allocated aircraft structure reliability requirement has been achieved.

b. Quantifying the accuracy of analyses. (par 5.4.1.2)
    i. The accuracy of the analyses described in par 5.2 (design) shall be probabilistically quantified by direct comparison to the test results described in par 5.2.14 (design development test) and par 5.3 (full scale testing) and documented to support aircraft structural certification.

c. Input:
    i. Risk analysis shall be performed and utilized in the initial airworthiness certification data.

d. Output:
    i. To determine the combined impact of all tailored ASIP tasks and/or elements on aircraft structure reliability and to verify that the allocated aircraft structure reliability requirement has been achieved.
    ii. The accuracy of the analyses described in par 5.2 (design) shall be probabilistically quantified by direct comparison to the test results described in par 5.2.14 (design development test) and par 5.3 (full scale testing) and documented to support aircraft structural certification.

e. Inspection intervals (par. 5.4.3.2.1)
    i. The initial inspections for fail-safe design concepts shall be established based on either: 1) fatigue analyses and tests with an appropriate scatter factor, or 2) slow damage growth analyses and tests assuming an appropriate initial flaw size.
    ii. The initial inspection for slow damage growth design concepts shall occur at or before one-half the life from the assumed maximum probable initial flaw size to the critical flaw size.
    iii. The repeat inspection intervals for both design concepts shall occur at or before one-half the life from the minimum detectable flaw size (based on the probability of detection) to the critical flaw size.
    iv. The risk analysis of par 5.2.16 and par 5.5.6.3 should be used to determine if a reduction in the inspection intervals are required to control the safety risk to an acceptable level or to reduce economic or availability consequences associated with damage

f. Input:
    i. The initial inspections for fail-safe design concepts shall be established based on either: 1) fatigue analyses and tests with an appropriate scatter factor, or 2) slow damage growth analyses and tests assuming an appropriate initial flaw size.
    ii. The initial inspection for slow damage growth design concepts shall occur at or before one-half the life from the assumed maximum probable initial flaw size to the critical flaw size.

iii. The repeat inspection intervals for both design concepts shall occur at or before one-half the life from the minimum detectable flaw size (based on the probability of detection) to the critical flaw size.

g. Output:

i. The risk analysis of par 5.2.16 and par 5.5.6.3 should be used to determine if a reduction in the inspection intervals are required to control the safety risk to an acceptable level, or to reduce economic, or availability consequences associated with damage repair.

3. Risk Analysis Updates (MIL-STD-1530C par 5.5.6.3)

a. The risk analyses described in par 5.2.16 (Initial Risk Analysis) and par 5.4.1.1 (Risk Analysis) shall be updated and the results shall be reported for formal acceptance using MIL-STD-882 direction. The EIFS distribution developed under par 5.3.4 (Durability tests) shall be updated to include aircraft inspection results (e.g., sizes of cracks found and number of locations inspected) which account for the IAT data described in par 5.5.1 (IAT program) to determine the probability of failure of the aircraft structure. Validation of the EIFS distribution by teardown inspection of aircraft and/or components with high levels of predicted damage shall be considered. The primary reasons to update the risk analyses are to:

i. Evaluate detected and anticipated aircraft structural damage. The results shall be used in conjunction with IAT data described in par 5.5.1 to establish the individual aircraft maintenance times.

ii. Evaluate economic and/or availability impacts associated with maintenance options such as inspection and repair/replacement as needed versus modification.

iii. Determine the structural integrity risk associated with operating the aircraft beyond the design service life.

b. These updates shall be used to compare the predicted probability of catastrophic failure of the aircraft structure to the following limits. A probability of catastrophic failure at or below 10^{-7} per flight for the aircraft structure is considered adequate to ensure safety for long-term military operations. Probabilities of catastrophic failure exceeding 10^{-5} per flight for the aircraft structure should be considered unacceptable. When the probability of failure is between these two limits, consideration should be given to mitigation of risk through inspection, repair, operational restrictions, modification, or replacement. Corrosion impact to the life and risk should be incorporated within the framework.

c. Input:

i. The risk analyses described in par 5.2.16 (Initial Risk Analysis) and par 5.4.1.1 (Risk Analysis) shall be updated and the results shall be reported for formal acceptance using MIL-STD-882 direction.

ii. The EIFS distribution developed under par 5.3.4 (Durability tests) shall be updated to include aircraft inspection results (e.g., sizes of cracks found and number of locations inspected) which account for the IAT data described in par 5.5.1 (IAT program) to determine the probability of failure of the aircraft structure.

iii. Validation of the EIFS distribution by teardown inspection of aircraft and/or components with high levels of predicted damage shall be considered.
iv. Actual load spectrum from IAT should be used to update the load input

d. Output: Consider a probability of catastrophic failure at or below 10^{-7} per flight for the aircraft structure is considered adequate to ensure safety for long-term military operations. Probabilities of catastrophic failure exceeding 10^{-5} per flight for the aircraft structure should be considered unacceptable. When the probability of failure is between these two limits, consideration should be given to mitigation of risk through inspection, repair, operational restrictions, modification, or replacement. The primary reasons to update the risk analyses are to:
    i. Evaluate detected and anticipated aircraft structural damage. The results shall be used in conjunction with IAT data described in par 5.5.1 to establish the individual aircraft maintenance times.
    ii. Evaluate economic and/or availability impacts associated with maintenance options such as inspection and repair/replacement as needed versus modification.
    iii. Determine the structural integrity risk associated with operating the aircraft beyond the design service life.

For these three major risk assessment tasks, the input parameters required are summarized in the following table.

Table B-1. Input Parameters for Various Risk Assessment Tasks

Input Parameters	5.2.16	5.4.1	5.6.3
K/sigma vs a file	Selected design load and material	Full scale test results	IAT Actual
Fracture toughness distribution	Selected material allowables	Full scale test results	IAT Actual
Initial crack size distribution	Historical data	Full scale test results 5.3.4	IAT track data to update data from 5.3.4
a vs T file	Selected design load and material	Full scale test results	IAT Actual
Max stress Gumbel Dist. (loads exceedance curve)	Design Load	Design Load	IAT load
POD parameters	NDI program	NDI program	NDI program
Repair crack size distribution	As good as new	As good as new	As good as new
Inspection number and time	Based on 5.4.3.2.1 criteria	Based on 5.4.3.2.1 criteria	Based on 5.4.3.2.1 criteria
Number of locations per airframe	Selected Design	Selected Design	IAT updated
Number of airframes in the fleet	Selected Design	Selected Design	IAT updated

To conduct the risk assessment calculation for the above cases, it is essential that the structural analysis models be sufficiently accurate to provide confidence in the information generated by

any risk assessment. Figure B-1 summarizes a software package (PRObability of Fracture, PROF) – Ref [16], developed by the University of Dayton Research Institute, that is frequently used by the USAF to estimate the probability of failure for cracked structure. A similar tool "Reliability Based Design and Maintenance System (RBDMS)" was developed by The Boeing Company to solve similar problem using the same analysis process and data but using different probabilistic analysis strategy and different ways to manage the statistical distributions.

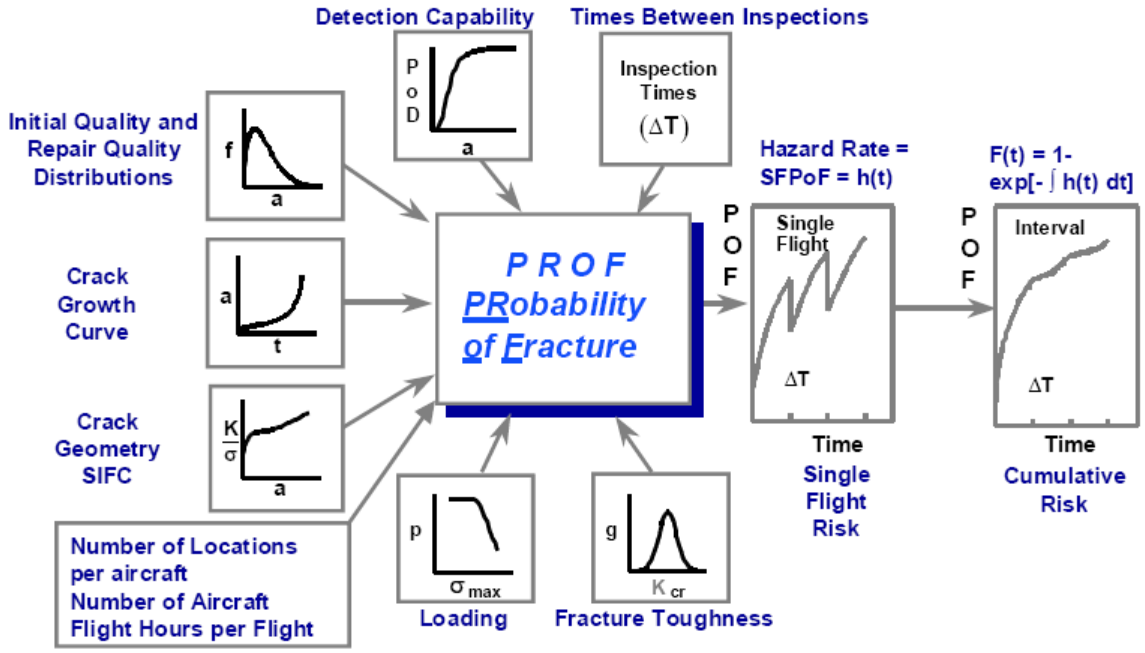


Figure B-1. Risk Analysis Input parameters and single flight probability of Failure (SFPoF)

Based on the current set-up, PROF (or RBDMS) can be used to estimate the risk with limited difficulty. However, when the problem becomes more complex, i.e., more random variables need to be considered, the proposed PROF (or RBDMS) code may not be able to solve the risk accurately. Furthermore, when dealing with other failure modes in addition to the crack growth model, the proposed PROF code may not be useful and therefore, a more robust probabilistic module may be needed. Boeing has developed an in-house probabilistic analysis and design core module "Finite Element Based RELiability" (FEBREL) as shown in Figure B-2 that can be used to solve a suite of problems with different number of failure modes and different number of random variables. This capability is essential for risk analysis estimates of complex problems.

To effectively communicate risk analysis results, it is important to ensure that common expressions and definitions are used. The Single Flight Probability of Failure and the Cumulative Distribution Function are expressions that are routinely utilized in the USAF and are defined as: The Single Flight Probability of Failure (SFPoF) is the instantaneous risk at some time in the aircraft life and is frequently referred to as the hazard rate. Another way to state this is the probability of failure in the flight given that a failure has not previously occurred. Mathematically the SFPoF is given by the probability density function divided by one minus the cumulative distribution function. The Cumulative Distribution Function (CDF) is the probability of failure in any flight before a given time. This can be used to compute the probability of failure

after a given number of flights for a single aircraft or a group of aircraft. It can also be used to estimate the number of expected losses for a group of aircraft.

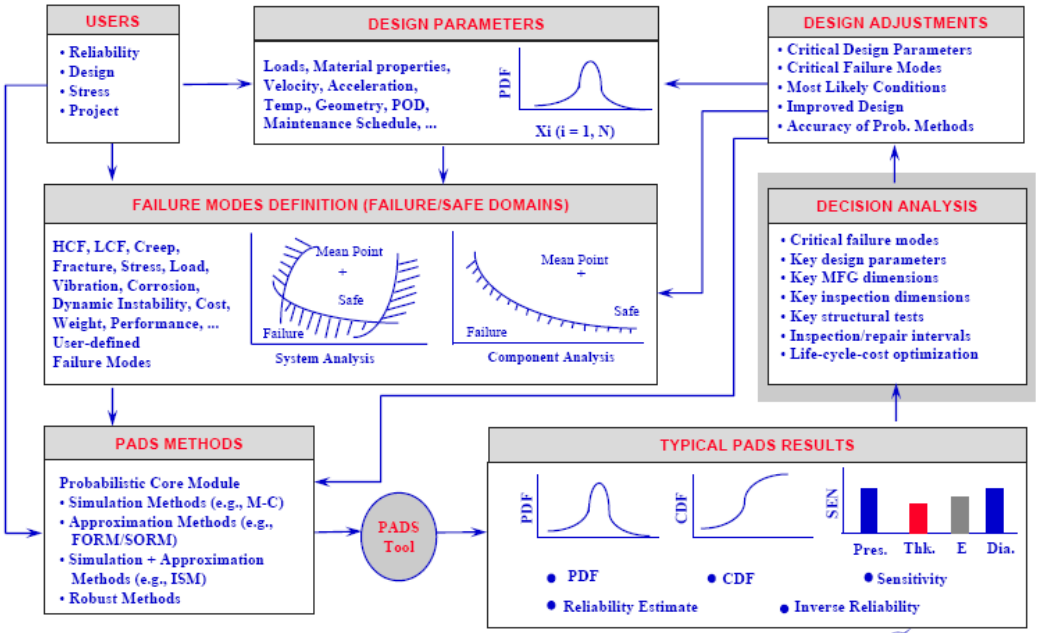


Figure B-2. Boeing's FEBREL Code Analysis Strategy

JSSG-2006 provides guidance on the maximum allowable probability of detrimental deformation and structural failure. For design guidance, this is limited to cases where deterministic values have no precedence or basis. JSSG-2006 states the maximum acceptable frequency of the loss of adequate structural rigidity, or proper structural functioning, or structural failure leading to loss of the air vehicle is 1 x 10^{-7} occurrences per flight. The USAF practice for risk thresholds has historically been:

(1) A SFPoF < 10^{-7} is adequate for long-term operations.
(2) Limit the exposure when the SFPoF is between 10^{-7} and 10^{-5}.
(3) A SFPoF > 10^{-5} is considered unacceptable.

The above criteria can also be seen in MIL-STD-1530C section 5.5.6.3.

B.2 Additional ASIP Risk Assessment Requirements

Additional risk assessment requirements are required to incorporate other CBM+ technologies and concepts specifically technologies such as Structural Health Monitoring (SHm) which is considered as part of the developed strategy and demonstration. The key objective of SHm is to detect the crack which is the similar to Non-Destructive Inspection (NDI) technologies, in fact in some instances SHm is referred to as on-board NDI; however, SHm will be able to detect the crack on a continuous monitoring basis which provides an important capability to mitigate missing a unexpectedly large crack between regular NDI inspections or an unexpected crack growth issue.

For the proposed CBM+SI, two SHm capability options are considered and discussed below.

1. Option #1 – "Boolean" crack sensor – see Figure B-3

a. Detect presence of any crack within a predefined area that is greater than or equal to a predefined length
b. Lower fidelity but "easier" to implement in a short time period
c. Potential extend the single zone to multiple zones (see Figure B-3), i.e., more than one predefined crack size; however, the probability of detection for each crack size may be different.
d. This option is easier to implement, over the high fidelity crack sensor discussed in the next section; thus, it is possible to consider this intermediate "fidelity" approach for the demonstration phase.
e. These SHm approaches will be considered as part of the risk assessment process and the effect of the different methods on the risk estimates will be documented.

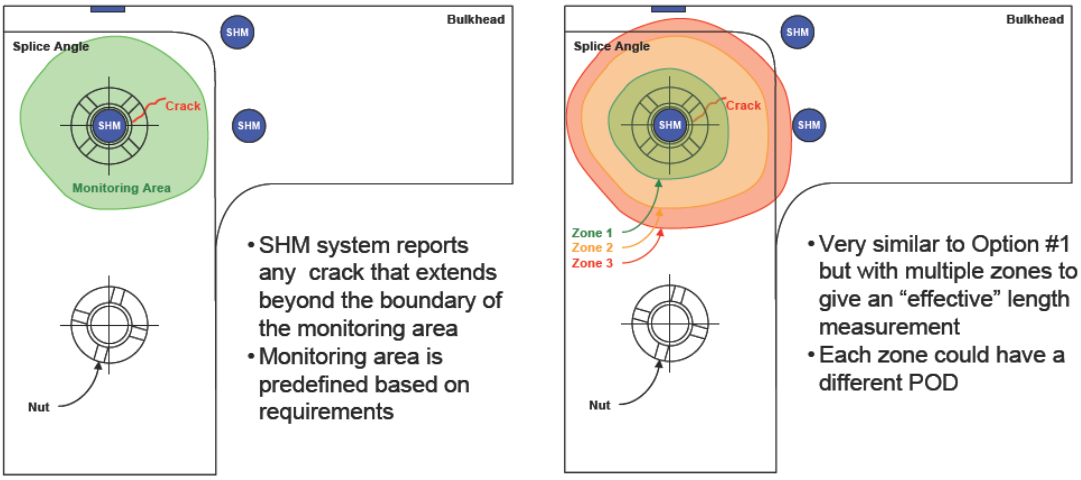


Figure B-3. Boolean Type of SHm – Single Zone and Multiple Zones

2. Option #2 – "high fidelity" crack sensor – see Figure B-4
    a. Detect presence, orientation, and size of any crack within a predefined area to a predefined level of precision
    b. Higher fidelity but more challenging to implement
    c. The output of this high fidelity SHm is equivalent to traditional NDI. In other words, a POD model can be developed.
    d. To develop the POD model requires data and two options of data are considered:
        i. Experimental data – limited quantities
        ii. Simulated data – must be validated by test
    e. This option may not be available for the demonstration example due to its complexity and budget constraint. Technology gaps for this option will be identified and summarized.
    f. From risk assessment, this option should also be considered because this is considered a possible eventual goal for SHm technology.

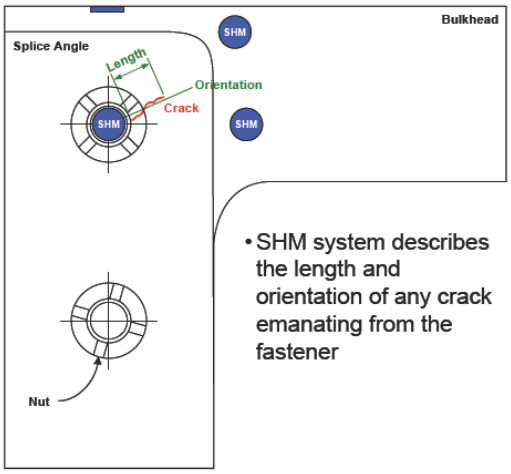


Figure B-4. High Fidelity SHm Option

From the above two SHm options, their corresponding output to the risk assessment analysis process must be defined properly. The following are the summary of the outputs requirements for both SHm options:

1. Option 1: Boolean type of SHm
    a. Single zone: one detectable crack size with probability of detection 100% (or a specified POD)
    b. Multiple zones: several detectable crack sizes with corresponding probability of detection for each crack size. The largest one will be the same as the single zone case, i.e., 100% (or a specified POD). For the other crack sizes, the probability of detection may be different.
2. Option 2: NDE POD type of SHm – High fidelity SHm
    a. The capability of SHm is assume equal to the traditional NDI. The probability of detection curve can be developed and defined for this high fidelity SHm option. Based on the capability, the output of this type of SHm will be the location, direction and the size of the detected crack.

With these additional SHm capabilities, it is important to understand how to integrate this additional information, and uncertainty into the risk assessment analysis. In the following, the current risk assessment analysis process and updated analysis process with SHm will be discussed in subtask 1.1.1.3 “Data Flow”.

1. The original risk assessment analysis process can be seen in Figure B-5. A step-by-step analysis procedure is described below:
    a. The program first performs its crack growth analysis to the first selected time interval. The crack size distribution will start from the EIFS input and grows to an updated crack size distribution. This crack size distribution will then be used in calculating the SFPoF value. If the calculated SFPoF value is less than the prescribed threshold, 1.E-7, (defined from MIL-STD-1530C), the crack will continue to grow until it reaches this limit. In addition, the risk assessment analysis process is shown in Figure B-5. The process will continue until the crack grows to a size where its SFPoF is very close to the threshold value. The time it reaches the limit will be posted and recorded.

b. At that time, the updated crack size distribution will then be used to calculate the percentage of crack found based on the input NDI POD parameters. Then, the crack size distribution after inspection will be created based on the percentage of crack found and not found.
c. After the inspection step, the updated crack size distribution will have to perform the crack growth analysis again and its corresponding SFPoF will also be calculated until it reaches the required risk limit of 1.E-7 again. The process will then be repeat itself until the selected number of inspections has been reached.

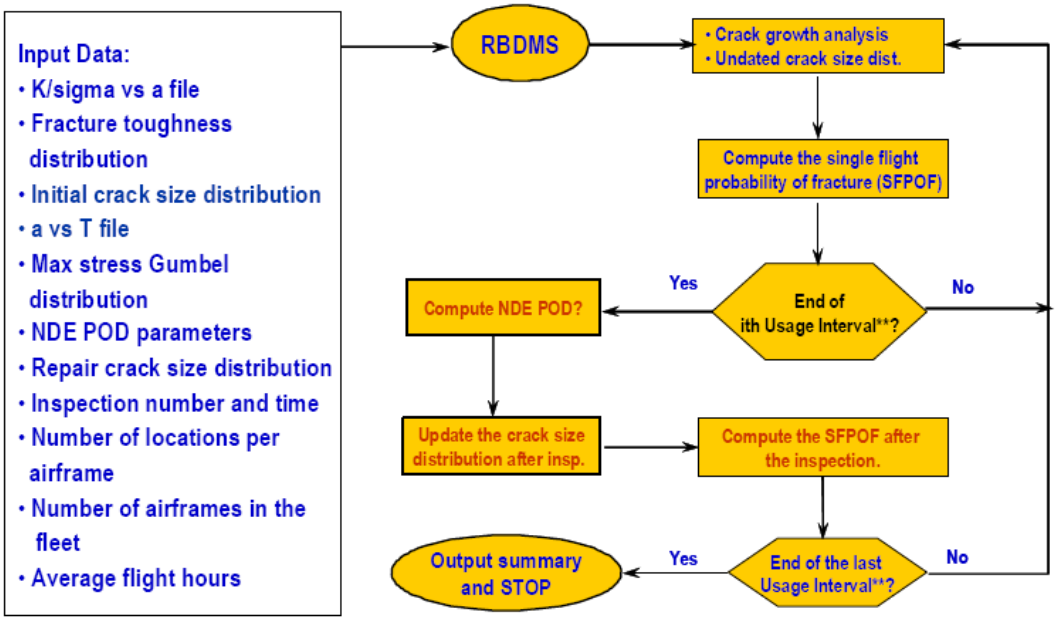


Figure B-5. Risk Assessment Analysis Process

2. With the addition of SHm, the current risk assessment process will not be changed but it may increase the analysis iterations as shown in Figure B-6. When there are no cracks found before the end of selected inspection interval, NDI will be performed as usual. However, when a crack is found before the end of inspection interval, the following potential steps will be added:
    a. Based on the detected crack size and time to detect the crack size, first question: Is the crack size large enough to be repaired? Second question: Is the probability of detection small enough to be rechecked by using NDI? This step needs to be pre-defined based on bulkhead repair requirements (the requirements must be discussed and defined with F-15 and SHm experts). Basically, from the above two questions, four options can be considered:
        i. If it is big with high POD, it requires immediate attention; perform repair immediately.
        ii. If it is big with low POD, it requires immediate attention. Perform NDI to check if crack exist, if yes, then perform repair immediately.
        iii. However, if it is defined as a small crack but with a high POD, then no repair will be done.

iv. However, if it is defined as a small crack but with a low POD, then NDI may be required again to confirm the crack size. If small, then no repair will be done.

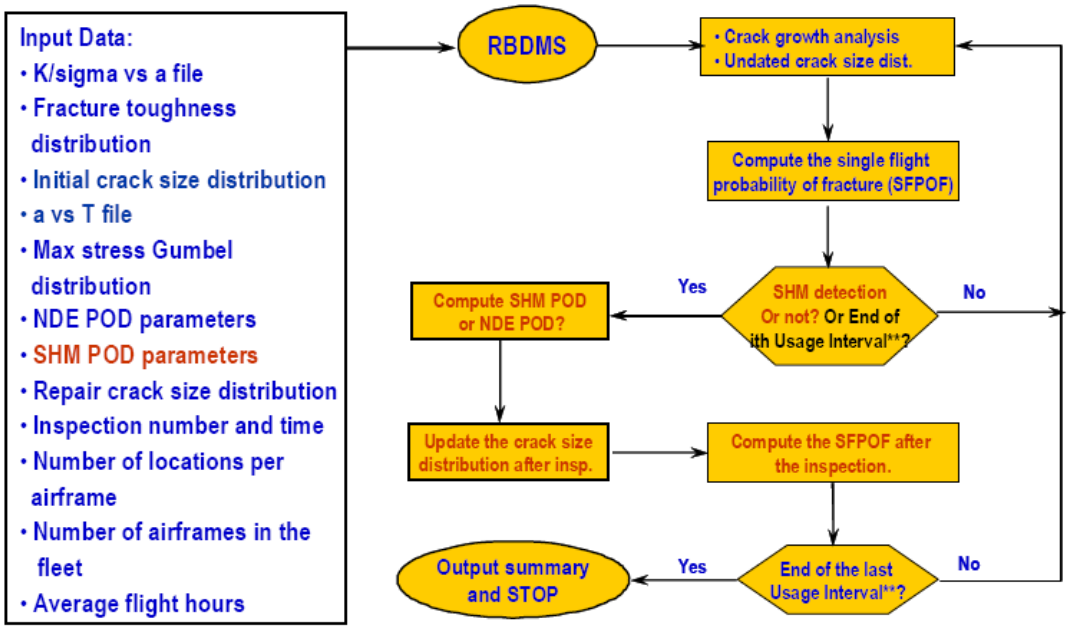


Figure B-6. Risk Assessment Engineering Analysis Process with SHm Addition

b. With the above options, the next step is how to link up with the current risk assessment process again.
   i. How to update the crack size distribution?
      - With a detected crack size at the given time, assume the crack has been repaired, then, the crack size should be updated based on the SHm POD curve model.
      - Without the repair case, the crack size distribution won't be updated and the same inspection schedule should remain but an additional check for the time to failure based on the detected crack size and crack growth curve (with a safety factor of 2). Whichever of the two values are smaller will be used as the next inspection interval**.**
   ii. How to determine the next inspection interval?
      - When repair action is taken, the next inspection interval must be revised based on the updated crack size distribution.
      - When repair action is not taken, the next inspection interval must remain the same or the time to failure based on the detected crack size and crack growth curve (with a safety factor of 2). Whichever of the two values are smaller will be used as the next inspection interval.
   iii. Do we have to perform NDI again at the scheduled inspection interval?
      - NDI and repair at the time of inspection can be performed when it reaches the inspection time where the risk may reach 1.E-7. The

reason for this is to validate and gain confidence in the SHm system, while at the same time maintaining the safety of the fleet.

iv. Do we have to calculate the SFPOF based on the updated crack size distribution?
    - Yes, this part of the analysis will always remain the same. As long as there is an updated crack size distribution, it will continue to grow with time and SFPOF will always be calculated accordingly.

v. How to keep track of the small cracks?
    - When a crack was found but it is too small to repair, the data should be used to serve the following purpose: Validate the crack growth model, calculate the time to repair based on deterministic crack growth model and compare with the time determined by using the risk criterion.

B.3 Diagnostic Capability Requirements

The key diagnostic tasks from the ASIP side for CBM+SI are IAT Program and L/ESS. In the following, the requirements in MIL-STD-1530C for these two tasks are summarized below.

IAT Program Requirements

Section 5.4.5, Individual Aircraft Tracking (IAT) Program development

A program to perform individual aircraft tracking shall be developed to obtain actual usage data that can be used to adjust maintenance intervals on an individual aircraft ("by tail number") basis. All force aircraft shall have systems that record sufficient usage parameters that can be used to determine the damage growth rates throughout the aircraft structure. The systems shall have sufficient capacity and reliability to achieve a 90-percent minimum valid data capture rate of all flight data throughout the service life of the aircraft. The systems shall include serialization of interchangeable/replaceable aircraft structural components, as required. The IAT Program shall be ready to acquire data at the beginning of initial flight operations. If instrumentation and/or sensors are part of the IAT Program, the instrumentation shall be incorporated into the full-scale static test described in Section 5.3.1, into the full-scale durability test described in Section 5.3.4, and into the flight and ground loads survey aircraft described in Section 5.3.3.1. Data systems should comply with the requirements of AFPD 63-14 and AFI 63-1401.

Section 5.4.5.1 Tracking analysis methods

Analysis methods shall be developed which adjust the inspection and modification times based on the actual measured usage of the individual aircraft. These methods shall have the ability to predict damage growth in all critical locations and in the appropriate environment as a function of the total measured usage, and to recognize changes in operational mission usage. The methods shall also provide the ability to determine the equivalent flight hours. The analysis methods and accompanying computer programs shall be provided to the USAF.

Section 5.5.1 Individual Aircraft Tracking (IAT) Program

The IAT Program shall be used to adjust the inspection, modification, overhaul, and replacement times based on the actual, measured usage of the individual aircraft. The IAT Program shall be used to determine damage growth in the appropriate environment as a function of the total measured usage and to quantify changes in operational mission usage. The IAT Program shall also determine the equivalent flight hours (or other appropriate measures of damage such as landings, pressure cycles, etc.) and adjust the required maintenance schedule for all critical

locations on each individual aircraft. The IAT Program shall forecast when aircraft structural component life limits will be reached. Data systems should comply with the requirements of AFPD 63-14 and AFI 63-1401.

L/ESS Requirements

Section 5.4.4 Loads/Environment Spectra Survey (L/ESS) development.
A system to perform a loads/environment spectra survey (L/ESS) shall be developed to obtain actual usage data that can be used to update or confirm the original design spectrum. A sufficient number of aircraft shall be instrumented to achieve a 20-percent valid data capture rate of the fleet usage data. L/ESS systems shall record time-history data such as vertical and lateral load factors; roll, pitch and yaw rates; roll, pitch, and yaw accelerations; altitude; Mach number; control surface positions; selected strain measurements; ground loads; aerodynamic excitations; etc. Data shall also be collected to characterize the thermal and chemical environments within the aircraft and associated with aircraft basing. If the IAT Program as described in Section 5.4.5 obtains sufficient data to develop the baseline operational loads/ environment spectrum and to detect significant changes in usage and/or environment, a separate L/ESS system as described herein is not required. If instrumentation and/or sensors are part of the L/ESS Program, the instrumentation shall be incorporated into the full-scale static test described in Section 5.3.1, into the full-scale durability test described in Section 5.3.4, and into the flight and ground loads survey aircraft described in Section 5.3.3.1. Data systems should comply with the requirements of AFPD 63-14 and AFI 63-1401.

Section 5.5.3 Loads/Environment Spectra Survey (L/ESS)
The loads/environment spectra survey shall be conducted to obtain actual usage data that can be used to update the original design spectrum. A new baseline operational loads spectrum shall be developed from the in-flight measurements and the predicted operational environment updated as necessary. Significant changes to the baseline operational loads spectrum shall be used to update the analyses described in Section 5.5.5. Data systems should comply with the requirements of AFPD 63-14 and AFI 63-1401.

Section 5.5.3.1 Initial Loads/Environment Spectra Survey
The initial survey period shall last for at least 3 years after Initial Operating Capability (IOC). The length of the initial survey period shall be based on evaluations of the mission types, mission mix, and quantity of aircraft in service.

Section 5.5.3.2 Loads/Environment Spectra Survey updates
The stability of mission types, mixes, and severity shall be evaluated to determine the need for periodic survey updates. The ASIP Manager shall review the need for L/ESS updates annually.

APPENDIX C. Requirements for the Structural Health Monitoring System For the F-15 Fuselage Station 626 Bulkhead - *DRAFT*

C.1 Introduction

This appendix presents the requirements for a crack detection Structural Health Monitoring (SHm) system for the F-15 airplane fuselage station 626 bulkhead.

On the lower portion of the bulkhead, there is a built-up of materials where it attaches to a longeron and skin. In addition, there is also a splice plate on the inner service (see Figures C-1 & C-2). Cracks have been found in the bulkhead that inspections have indicated are initiated on the section of the bulkhead flange hidden within the stack-up of these parts. By the time the crack is visible on a part of the bulkhead flange that is exposed, it may be too large for any type of repair. If this is the case the aircraft may be retired, as the replacing of the whole bulkhead can be cost prohibitive.

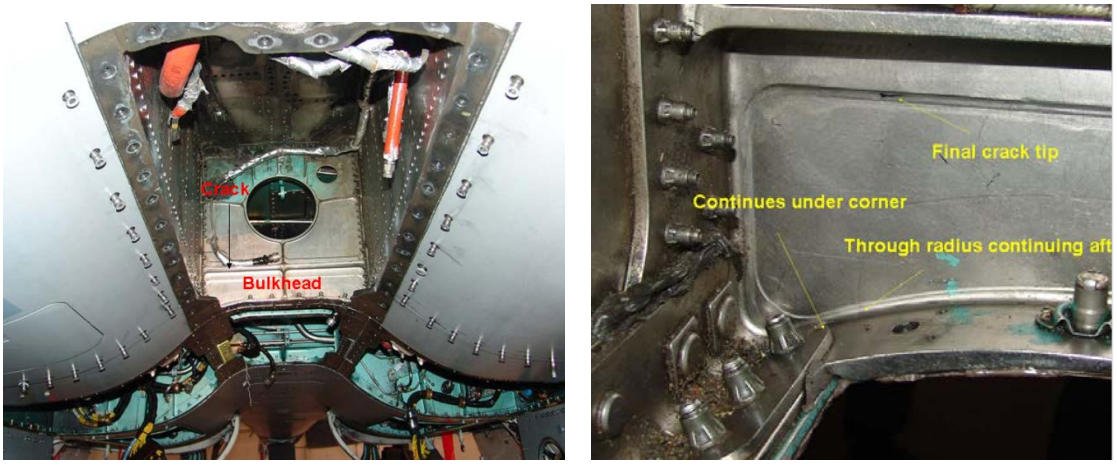


Figure C-1. Pictures of the FS626 Bulkhead and where cracks have been found

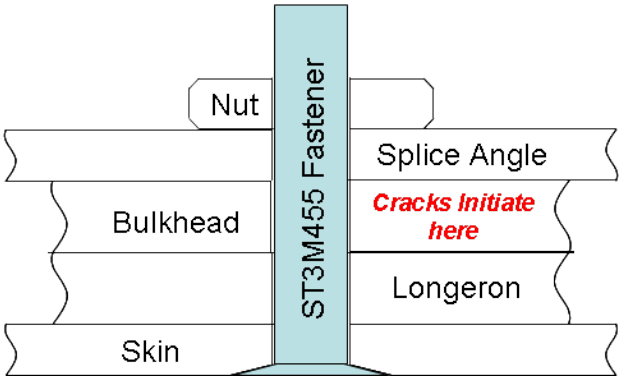


Figure C-2. Stack-Up illustration

The purpose of a crack detection SHm system would be to autonomously detect the presence of a crack and/or measure the dimensions of a crack in the above mentioned location.

The current Non-Destructive Inspection (NDI) techniques used to inspect the crack consist of standard practices and are highly reliable. However, the current inspection processes are very time intensive resulting in increased support costs and decreased asset availability. Furthermore, if the crack is found too late, it may be unrepairable resulting in the need to replace the bulkhead. This can result in early retirement of the aircraft due to the prohibitively high cost of replacing the bulkhead.

Remote condition-based SHm systems have the potential to increase the value of flight vehicles by reducing costs associated with manual inspection time and increasing the frequency of inspections to avoid not finding cracks until they are too large to repair. As the current maintenance techniques ensure the safety of flight vehicles; SHm systems shall not degrade this capability.

This specification provides the requirements for a structural health monitoring system for crack detection in the F-15 FS 626 Bulkhead. The requirements contained in this document are intended to define the expected functions of structural health monitoring system, and to provide guidelines that ensure that the system can adequately perform those functions.

For requirements with numerical limits, a threshold value and an objective value exist. The threshold value is the minimum acceptable value, and the objective is the desired target. A summary table (Table C-1) containing the numerical thresholds and objectives referenced in the text is provided at the end of the document.

C.2 Scope

This document defines the requirements for a structural health monitoring system for the F-15 FS 626 bulkhead.

C.3 Safety

C.3.1 The design of the system shall be capable of sustaining a failure and retaining its hardware and energy so that no injury to personnel or damage to the flight vehicle is caused.

C.3.2 Safety of flight. The system shall maintain or improve the existing level of safety of flight. Under no circumstances shall the system degrade the safety of flight.

C.3.3 A safety of flight analysis and certification will be performed prior to flight.

C.4 System Function and Performance

The system functional and performance requirements are primarily based on comparisons with conventional non-destructive inspection methods and capabilities determined during discussions with representatives of the Boeing F-15 Program.

Both bolt hole eddy current and surface eddy current methods are currently employed to find cracks. The bolt hole eddy current and surface eddy current methods are expected to find a 0.05" X 0.05" crack with 90/95 probability of detection. Boeing did not conduct this study, the USAF has supplied this to the F-15 program and the Boeing NDI experts concurred that this was obtainable. However, the USAF would have liked to use 0.03" X 0.03", but did not have a POD study to validate that flaw size

The crack has been shown to grow behind an embedded region – a region of the bulkhead between the splice plate and longeron. Visual inspections are not possible when the crack grows

in a hidden region. Eddy current inspections are also complicated. In-situ SHm offers the capability of continued inspection as the crack grows in the hidden area.

The performance requirements for the SHm system on the station 626 bulkhead in the F-15 aircraft are:

C.4.1 The system shall monitor the existence of a crack in a series of concentric zones as notionally depicted in the shaded regions illustrated in Figure C-3. The extent of each zone shall be based on critical crack lengths predetermined via durability and damage tolerance analyses. The system shall detect the existence of a crack within an existing zone to a predetermined Probability of Detection (POD) level. The limits on this requirement are provided in Table C-1.

C.4.2 The system shall monitor the condition of the repair itself. During component testing, it was found that a crack can initiate and grow in the radius of the repair. If this crack occurs, the system will detect the existence of a crack within an existing zone to a predetermined Probability of Detection (POD) level. The limits on this requirement are provided in Table C-1.

The system shall quantify the uncertainty associated with any measurement it takes.

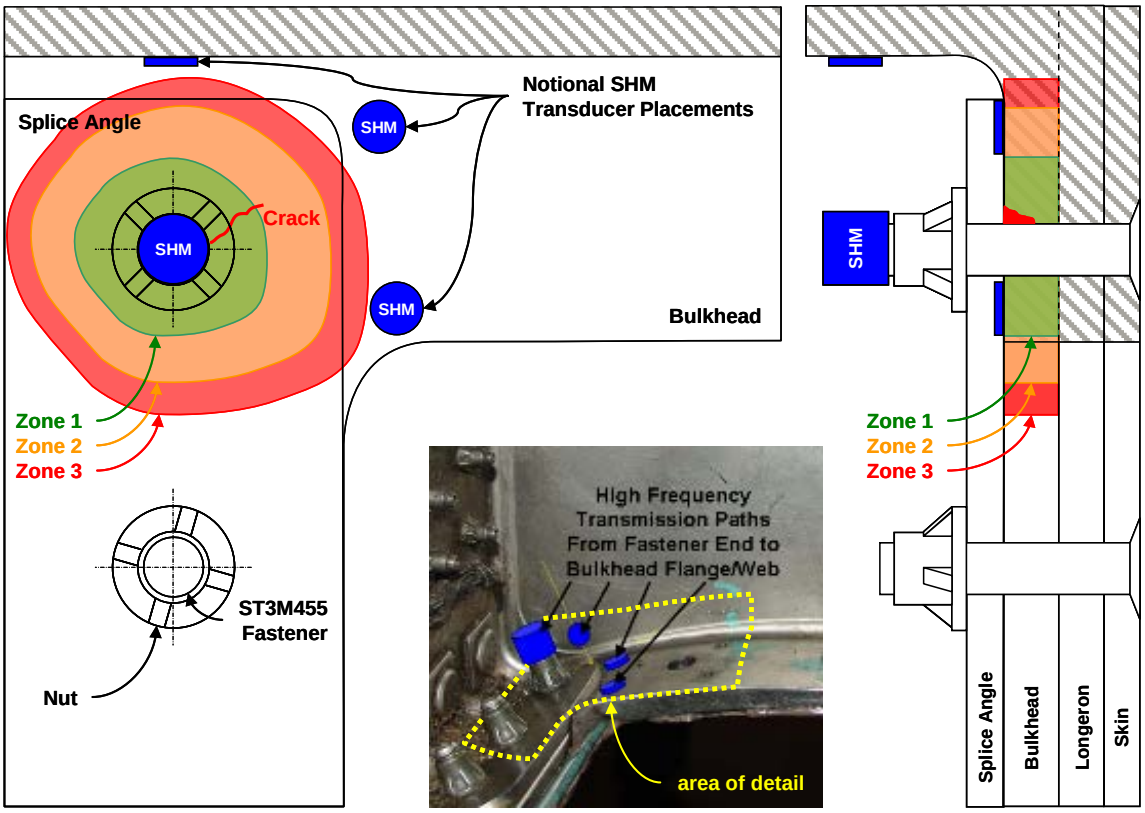


Figure C-3. Notional crack monitoring system layout and detection zones (NOT TO SCALE)

C.5 Interfaces

C.5.1 Mechanical

C.5.1.1 The on-airplane system shall be compatible with the host structure that it is designed for, including high and room temperature cure adhesives and two-part epoxy systems.

C.5.1.2 Clearances: The sensor and connectors shall not interfere with the operation of any other system or subsystem; a minimum clearance as shown in Table C-1 shall exist between any portion of the on-board sensor and any adjacent structure.

C.5.2 Thermal

C.5.2.1 Structural or ambient temperatures between -65 degrees Fahrenheit (-54 Celsius) and +160 degrees Fahrenheit (61 Celsius), and temperature change rates of 3.75 degrees Fahrenheit (2.1 Celsius) per second within that range, shall not degrade the performance of the system. This temperature range is still being verified with the F-15 program.

C.5.2.2 Thermal expansion effects shall not degrade the performance of the system; the system shall be able to meet the requirements in this document after thermal expansion or contraction has occurred.

C.5.3 Structural

C.5.3.1 The system shall not adversely affect the load path between the repair and the host structure.

C.5.3.2 Strength and Stiffness

C.5.3.2.1 On-board systems shall be designed to withstand the maximum structural environments for which the host structure was designed, including safety factors. Applicable environments include humidity, fungus, salt fog, sand and dust, acceleration, and vibration.

C.5.3.2.2 Deflection of the host structure at design ultimate load shall not adversely affect system functionality.

C.5.3.2.3 Sufficient structural rigidity shall be provided so that deflections that would jeopardize the proper functioning of any flight equipment shall be avoided. Deflections shall not violate critical clearance requirements or cause physical separation of any preloaded joints.

C.5.4 Flammability

C.5.4.1 Electrical shorting or other energy discharge of the system shall not ignite fuel vapors or other flammable materials.

C.5.4.2 The temperature of the components shall not reach the auto-ignition temperature of JP4 or JP8 fuel (435°F, or 224°C).

C.5.4.3 The flight hardware shall not provide a method of arcing or sparking.

C.5.5 Electro-mechanical

C.5.5.1 Use of electrical connectors shall not degrade the bond attaching the sensor to the structure. Compliance with this requirement can be demonstrated by passing a connector abuse test.

C.6 Design Life

C.6.1 The design life for the system applied to the F-15 station 626 bulkhead shall be equal to the life of the aircraft. This requirement applies to systems installed on the flight structure and to systems in storage.

C.6.2 The system shall meet all performance requirements over the design life.

C.6.3 The design life shall be used as the basis for qualifying the relevant parts, materials, and assemblies.

C.6.4 There is no requirement for the sensor to survive removal from the structure. Removal is expected to be destructive to the sensor. The structure and finish under the sensor adhesive layer must remain undamaged after removal of the sensor layer.

C.7 Reliability

C.7.1 A failure modes and effects analysis should be performed to guide reliability requirements. To meet the reliability requirement, the testing defined in the reliability test plan shall be successfully completed.

C.8 Mass

C.8.1 Mass of the on-airplane portion of the health monitoring system will be minimized. Flight components are defined as sensors, sensor interconnect wiring, connectors, connector covers, protective overlayers, and epoxy. The maximum mass of the flight components of the system will be as defined in Table C-1. This mass is for each side (left and right) of the airplane. For an installation with sensors on both sides of the airplane, the total mass allowed is twice the amount shown.

C.8.2 While there is no specific requirement on mass of the off-board (data acquisition) portion of the system, that portion should be reasonably portable and suitable for convenient use in the field maintenance environment. This requirement should be updated if on-board data acquisition is required.

C.9 Electromagnetic effects

C.9.1 Monitoring systems shall not interfere with existing on-board electronic systems. As the system is designed to be operated when the aircraft is on the ground, this requirement is intended to minimize interference between the sensor/data acquisition system and other maintenance or ground data systems.

C.10 Repairability

C.10.1 The system hardware shall be repairable using normal shop tools.

C.10.2 Sensing elements or transducers may be located in inaccessible regions. The components of the system will be as serviceable as practical. Certain components may necessarily be placed in difficult to access areas.

C.11 Redundancy and fault tolerance

C.11.1 Redundancy shall be applied as required herein to eliminate critical failure modes, avoid single point failures if possible, and to improve reliability.

C.11.2 The system must be robust enough to withstand sensor failures. The requirements in this document shall be met with any one sensor or transducer element failed.

C.12 Degradation of structural capability

C.12.1 The system shall not degrade the structural capability of the host structure.

C.12.2 Sensor components may be bonded to the structure. For non-wireless systems, added penetrations in structure are not allowed without engineering authorization.

C.13 Contamination by fluids

C.13.1 The system shall not be degraded by exposure to water, fuels, hydraulic fluids, lubricating oils, solvents and cleaning fluids, de-icing and anti-freeze fluids, runway de-icers, insecticides, disinfectants, coolant dielectric fluid, and fire extinguishants. Testing need only be completed for fluids that the system will be exposed to over extended periods or intermittently (on a regular basis under normal operation or possibly seasonally over the life of the system). Other fluids can be evaluated based on analysis or previous determination of material compatibility.

C.13.2 Cleaning the structure prior to installing the sensor will necessitate removing any corrosion inhibiting compound. The sensor layer must be able to function after reapplication of the corrosion inhibiting compound following sensor installation.

C.14 Allowable Damage Limits

C.14.1 Any increases in allowable damage limits due to the presence of the system shall be validated by testing. There are no planned increases in allowable damage limits for the F-15 station 626 application.

C.15 Inspection Requirements

C.15.1 Additional maintenance requirements due to a condition-based health monitoring system other than gathering data are not acceptable.

C.15.2 After initial installation and checkout of the sensor system, no inspection requirements will exist for the system itself. It is acceptable for the data acquisition system to perform a self-check or sensor health check at each data collection interval.

C.16 Integration with Airplane Systems

C.16.1 The system shall be able to operate independent of other airplane systems.

C.17 Data bus requirements

C.17.1 The system will take data from the structure and process that data to provide feedback to the user. The user may be the operator, mechanic, crew, or another airplane system. No on-aircraft data bus is planned for the F-15 station 626 application.

C.18 Portable Maintenance Aids

C.18.1 On-board health monitoring systems shall interface with portable maintenance aids. This application is not considered on-board, as the data acquisition equipment is ground-based.

C.19 Open System Architecture

C.19.1 Once installed, the system shall allow addition or removal of sensing components without replacing any existing or original data bus.

C.20 Ease of Use

User friendliness is an important feature of the SHm system. Conventional NDI systems usually require specialized knowledge and skill to operate and interpret. One of the goals of the SHm system technology development is to improve upon the user-friendliness of existing NDI methods. User-friendliness is subjective, making this a difficult requirement to levy.

C.20.1 The user interface to the system shall be easy to understand and use for mechanics and support staff.

C.20.2 Wherever possible, language-independent symbology will be used to convey information.

C.20.3 No special training or skill will be required to use the SHm data acquisition equipment.

C.20.4 The connector for data collection shall be located in an easy to access area.

C.21 Energy Sources

C.21.1 Batteries, energy harvesters, or other energy sources shall meet all applicable requirements within this specification.

C.22 System power requirements

C.22.1The system shall have the capability to operate independent of the power system for the flight vehicle.

C.22.2 The data acquisition system should be self-powered and should not require a power source during data collection at the airplane. It is acceptable for the device to contain a battery that requires charging while the system is not in use.

C.23 Testing

Appropriate testing shall be performed to validate system performance before implementation. An appropriate test plan will be formulated and followed.

C.23.1 Criteria of success. The equipment shall be considered to have successfully completed the required tests in the test plan when the following conditions have been satisfied:

C.23.1.1 Operation throughout all tests shall be within the limits stated in the test plan.

C.23.1.1 No deterioration or degradation of performance has occurred which could, in any manner, prevent the system from meeting its functional requirements during service.

C.24 Ground (Off-Board) Systems

C.24.1 Ground systems, which are the data acquisition system in the application, shall interface with flight systems.

C.25 Workmanship

C.25.1 Workmanship shall be of the highest quality such that the design standards of the host structure and the repair are not degraded or changed. At all points during manufacturing, integration, test, handling, storage, and transportation, these design standards shall be maintained. Written process specifications and standards shall control all operations.

C.26 Interchangeability

C.26.1 All like parts shall have the same part number. Each equipment item shall be directly interchangeable in form, fit, and function with other equipment items of the same part number. The performance characteristics shall permit equipment interchange with a minimum of adjustments and recalibrations in order to avoid retesting. The equipment must be of the same qualification status and reliability to meet interchangeability requirements.

C.27 Labeling and Marking

C.27.1 Each component of the system shall be uniquely and clearly identified. Electrical connectors shall be labeled.

C.28 Information Control Requirements

C.28.1 Upon official authorization, the Information Owner will be identified. The Information Owner will document all sensitivity levels of the data from the SHm system. S/he will consider any U.S. or foreign government classified contract, program, or project information requirements first. For sensitive information, s/he will identify sensitivity. There will be ITAR/EAR and Customer/Supplier Security components.

C.29 Security

C.29.1 The Boeing Computing Security Requirements Manual will be reviewed for the minimum security requirements that computing asset owners are expected to implement to safeguard their asset(s). Details for implementing the manual in specific computing environments (e.g., UNIX, Desk Top, Windows, etc.) are included in the Computing Security Implementation Manuals (CSIMs). Specific care will be taken to ensure compliance to all ITAR/EAR security requirements.

C.30 Document Maintenance

C.30.1 This document is to be maintained by the authors as identified on the signature page of this document. Any revisions must be approved by all authors or the author's designees.

C.31 Requirements summary

Table C-1 contains the values referenced in the text above for the installation of a sensor system in the F-15 airplane.

Table C-1. Summmary of Requirements for SHm System

Requirement	Threshold	Objective
Detect crack in bulkhead: length > 0.120 inch	P=0.80 <TBD>	P=0.90 <TBD>
Detect crack in bulkhead: length > 0.060 inch	P = 0.70 <TBD>	P=0.80 <TBD>
Detect crack in bulkhead: length > 0.030 inch	P=0.60 <TBD>	P=0.60 <TBD>
Flight component mass (includes transducers, wiring and connectors)	100 grams (0.22 pounds)	25 grams (0.05 pounds)
Temperature limits	-65 to +160 F	-65 to +160 F
Temperature rate-of-change limit	3.75 F per second	3.75 F per second
Clearance between sensor and adjacent structure	0.25 inch minimum	0.25 inch minimum

APPENDIX D. Data Requirements for TPM Analysis

The main objective of this Appendix is to define the Technical Performance Measurements (TPMs) and the required data sets for evaluations between the baseline and CBM+SI-implemented configurations. In addition, the relationship between TPM and Total Life Cycle Systems Management (TLCSM) is also discussed. Note that the data requirements will then be used by the F-15 program to investigate if all the required data sets are available for the two competitive structural components (see Appendix E).

D.1 Define All the Data Required For CBM+SI

The three TPMs required for assessment are:

- Fleet Availability or Aircraft Availability Rate: This describes the readiness of the fleet by a percentage considered available for missions and not in any maintenance.
- Total Cost of Ownership: This is the total cost to own and maintain the platforms and weapons systems from cradle to grave. For the CBM+SI evaluation, the period will cover from first year of research and development to the last use of the fleet. Other ways to express this TPM include Return on Investment, Net Present Value, and Cash Flow.
- Maintenance Hours per Flight Hour: This is the average maintenance labor hours per flight hour. Another way to view the use of resources during operation is Resource Utilization.

The TPMs for the baseline, or current configuration of the platforms, will be compared with the TPMs for the platforms with CBM+SI configurations.

Required data for the assessment include historic reliability and maintainability (R&M) data on the F-15, especially on the intermediate wing spar and the FS 626 Lower Bulkhead. To understand the impact of these two structures, all 2-digit work unit code (WUC) data for the platform and the 5-digit WUC data for the structures are required. The R&M data should cover inherent failures, induced failures, no defect actions, cannot duplicates (CNDs), retest OKs (RTOKs), removals, labor hours for each action, and number of aborts. To understand the historic use of the F-15, other data needed are the number of missions and sorties, their durations, the fleet size, and accumulated flight hours at fleet and platform levels.

For costs, the required data are labor cost per maintenance hour, cost per repair type (unscheduled and scheduled), additional costs per operating year, cost per removal and replacement, and costs for different maintenance categories (organizational level: O-level, intermediate level: I-level or depot level: D-level). When the CBM+SI alternatives are evaluated, the costs to evaluate include their development, production, and sustainment.

Possible data sources include historic maintenance databases such as the Maintenance Operating Query System (MOQS), Reliability Maintenance Information System (REMIS), and maintenance cost experts. Data sources will need to be confirmed with Tony Krueger from the F-15 program and contacts from Warner Robins Air Force Base.

D.2 Relationship with TLCSM – TPM

Total Life Cycle Systems Management (TLCSM) is “the implementation, management, and oversight, by the designated Program Manager, of all activities associated with the acquisition,

development, production, fielding, sustainment, and disposal of a Department of Defense (DoD) weapon or materiel system across its life cycle" [Defense Acquisition Guidebook, November 2006]. So for a CBM+SI alternative, all activities from the acquisition of the technology to the disposal of it with the platform will need to be covered. The TLCSM has five key measurement that need to be covered [Memo from Under Secretary of Defense, Acquisition, Technology, and Logistics, November 25, 2005]. This section makes sure that the TPMs align with the TLCSM metrics, as shown in the following comparisons. Each defined TLCSM metric can be linked with the required TPMs.

- Operational Availability: This is the percent of time that a weapons system is available to sustain operations. Operational Availability is related to the Fleet Availability TPM for evaluation.
    - Link with TPM: Way to express Fleet Availability in operation
- Mission Reliability: This is the percent of weapons system meeting mission success objectives, such as a sortie, tour, launch, or destination reached. Though not really linked to the above TPMs, Mission Reliability can demonstrate the fleet effectiveness for the scheduled missions.
    - Link with TPM: One way to express Total Cost of Ownership and can be impacted by the use of maintenance resources
- Cost per Unit of Usage: This covers the operating costs per unit of usage, but this can include the life cycle costs from acquisition to disposal. This is another way to express Total Cost of Ownership. In addition, the amount of Maintenance Hours per Flight Hour can affect the overall ownership costs.
    - Link with TPM: Express part of Total Cost of Ownership and can be impacted by the use of maintenance resources
- Logistics Footprint: This deals with the required amount of logistics support for deployment, movement, and sustainment of weapons systems. The logistics can impact all three primary TPMs depending on available materials and personnel at the right place and right time.
    - Link to TPM: Can affect fleet availability if not enough supplies are in stock to minimize fleet down time and can affect Total Cost of Ownership
- Logistics Response Time: This is the average time to acquire Class IX parts from the time of demand to the satisfaction of the demand. The time to acquire parts can impact the downtime of the fleet and cost to sustain, thus impacting the Fleet Availability and Total Cost of Ownership.
    - Link with TPM: Can affect fleet availability from response times for supplies and can affect Total Cost of Ownership

APPENDIX E. Assessment of Inner Wing, Intermediate Spar and Frame Station 626 Bulkhead

The main objective of this Appendix is to summarize the investigation of the required data sets for TPM analysis which will be available for the two competitive structural components. Background, crack growth models, NDE methods, SHM application, and the current F-15 program application status of CBM+SI technologies or concepts are also discussed and included.

E.1 Background and Service Histories

Inner Wing, Intermediate Spar Lower Flange - The F-15 inner wing, intermediate spar has experienced over twenty in-service findings of cracks, which require intermediate spar replacement. In addition, the F-15A/B/C/D Full Scale Fatigue Test (FSFT) was stopped at 18,100 flight hours due to an intermediate spar flange failure. The cracks initiate in the fastener hole and propagate into the web. Final failure occurs when the web losses all load carrying capacity.

FS 626 Lower Bulkhead Flange at the Inboard Longeron - The F-15 has had five lower FS 626 bulkhead flange cracks, one of which has mothballed the aircraft permanently since the current repair costs are around $1M. One of the cracks was detected in the fillet radius at the edge of the longeron interface (this was the aircraft that has been mothballed) and the remaining cracks were found in the first fastener inboard of the longeron interface.

E.2 Crack Growth Models Maturity

Inner Wing, Intermediate Spar Lower Flange - Boeing F-15 Program has developed an extensive analysis package for this location due to the failures, including sophisticated FEMs and hand analysis to correlate with the known problems. The crack growth model for the intermediate spar is very mature. This model was used in the development of correlations with in-service cracking and the full scale fatigue test failure. Currently the F-15 Program relies only on the crack growth life in the web for the tracking system. This is the life once the cracked has already propagated from the hole to the flange the web, due to the complex analysis in determining how large the residual stresses are at the interference fit fastener hole and the complexity of the NDI.

FS 626 Lower Bulkhead Flange at the Inboard Longeron - For this location a special "p-Level" FEM (Mechanica) model was created, by the F-15 Program, to accurately determine the stresses and find any and all hot spots in the vicinity. A highly detailed 3-D model has been developed and is being used in the correlation with in-service cracking that has been found. The two locations that have been found cracked, were indicated to be the most critical locations in the region, validating that the model was able to accurately predict the critical locations. A detailed durability and damage tolerance analysis has been correlated with the known in-service cracks and a report was released by the program at the end of March, 2009.

E.3 NDI Methods Maturity

The NDI procedures for both critical locations use standard practice techniques and are highly reliable.

Inner Wing, Intermediate Spar Lower Flange – NDI Procedures for this location currently use ultrasonic methods. However, detection of a crack is difficult, due to the wing being sealed and filled with foam. Without removing the upper wing skin and foam, detection of a small crack is difficult or impossible. Once it has reached the web, the most likely way to detect the crack, the spar is not salvageable and requires the installation of a new intermediate spar. The cost of the part is insignificant to the number of labor hours required to drill and ream fastener holes to mate with the skin.

FS 626 Lower Bulkhead Flange at the Inboard Longeron - Both bolt hole eddy current and surface eddy current methods are employed to find cracks. Detection of cracking is tedious and laborious in the current state of standard NDI techniques.

E.4 Work with SHm

Currently the F-15 uses an Individual Aircraft Tracking Program (IATP) to monitor the damage at critical locations. Approximately seventy safety of flight locations are monitored and inspected based on the results of the IATP and the Force Structure Maintenance Plan (FSMP) philosophies. These inspections are based on the concept of an initial flaw, stemming from a material defect or a flaw induced during manufacturing, growing under damage tolerance conditions.

The F-15 has an Individual Aircraft Tracking Program, but no sensors for health monitoring directly on the aircraft.

Inner Wing, Intermediate Spar Lower Flange – Use of SHm will detect a crack that is repairable with an oversized fastener and save a great deal of labor and down time.

FS 626 Lower Bulkhead Flange at the Inboard Longeron - Use of SHm will significantly increase sensitivity of early crack detection and prevent scraping of an airframe.

E.5 Identify Data For TPM Assessment

A short summary on the main Technical Performance Measurements (TPMs), the data needs and sources, and their relationship with the Total Life Cycle System Management (TLCSM), as presented in Appendix D. The F-15 program and Warner-Robins can provide the historic F-15 reliability and maintainability data and costs at O-level and I-level, recorded from now to 5 years ago.

The TPM information is readily obtainable for the F-15. We have in-house capability to obtain this information and can obtain some data directly from Warner Robins. One of the near term goals is to have Warner Robins provide us with the cost to repair both the wing intermediate spar and the FS 626 bulkhead. They will provide us with material and labor costs.

E.6 Assess CBM+ 10 Concepts and Technologies Application Status

Current F-15 assessments:

- **Prognostic:** The F-15 uses the FSMP to provide inspection philosophy and criteria, and uses the IATP to determine when each individual aircraft requires inspection. This provides early detection of crack, prior to in-service failures, but does not always catch the cracking prior to growing beyond easy repair options.

- **Diagnostic:** No formal or special diagnostics exists for the F-15. Each issue is developed on an as need basis as it arises. This concept and technology needs to be incorporated into the F-15 daily routine.
- **Portable Maintenance Aids (PMAs):** The F-15 has limited use of PMAs. We have laptop computers used to download information, but this is limited to future transference to other equipment for diagnostics.
- **Interactive Electronic Technical Manuals (IETMs):** Boeing is currently using IETMs for the newer models of aircraft. The original models, F-15 A/B/C/D work under the paper based Tech Orders. This has been a future change desired by the USAF SPO, but funding issues has prevented the update.
- **Interactive Training:** Training, in several media presentations, exists for different aspects of the F-15 inspections, diagnostics, etc., but has not been converted to an interactive format. Training has been limited to providing a straightforward concept of the steps and processes necessary to maintain and provide safety to the airframe.
- **Data Analysis:** This does exist for the F-15, but has only recently been implemented. In large part, this implementation was the direct result of the recent F-15 mishap.
- **Integrated information systems:** No, this does not exist for the F-15.
- **Automatic Identification Technology (AIT):** This has been discussed, in many different formats, but has never been implemented into the F-15. Once again, funding has limited the implementation.
- **Reliability Centered Maintenance (RCM):** Boeing has always maintained an RCM program. Originally this was based on crack initiation concepts, but grew into using damage tolerance concepts as the USAF transferred into the DTA concept. The RCM analysis created the initial inspection requirements. All the original analysis was feed into an RCM process and inspection intervals, inspection methods, inspection sampling plans were derived from this process. Now, many of the main functions of the RCM analysis have been largely superseded by the FSMP. The FSMP has become the main driver for inspection concepts, philosophy, and calling out of required inspections. We still keep the RCM system up to date, but everything has been superseded since we developed a FSMP. Other concerns such as who is responsible for the availability, total flight hours per maintenance hours calculations, needs additional investigation.
- **Joint Total Asset Visibility (JTVA):** This data does not exist for the F-15 Program.

APPENDIX F. Structural Health Monitoring

The main objective of this Appendix is to discuss if SHm Technology can be applied to both F-15 structural components: Bulkhead (BH) and Intermediate Spar (IMS). The mature/confidence of SHm technology and what kind of data SHm can provide for risk assessment are also discussed. Finally, a status report on the Hot Spot program (a SHm project using BH for demonstration) is reported.

F.1 Assess the BH Or IMS (Information Gathering)

Several options exist for detecting cracks in the FS 626 Bulkhead Flange and the Inner Wing, Intermediate Spar. Specific technologies include continuity sensors (e.g., crack wires and Comparative Vacuum Monitoring, also called CVM, sensors), insitu eddy current sensors, and a variety of insitu piezoelectric-based ultrasonic (e.g., pitch-catch arrays, pulse-echo arrays, phase-arrays, ect.). Developing a Structural Health Monitoring (SHm) system for either location will require first gathering a detailed set of system-level requirements. These requirements will not only define the required level of accuracy and reliability, but also will address such topics as concept of operations, stay-out regions, compatibility and safety (e.g., using a high-voltage technique in a wet wing box), durability, interface controls, etc. These requirements, along with the AFRL/Boeing SHM Design Framework, are used to develop and trade various SHm system designs.

Based on preliminary trade studies, it was determined that an insitu piezoelectric-based ultrasonic system would meet most, if not all, known requirements and have the best ability to locate and size cracks for the bulkhead hot spot. Note that the solution developed for the bulkhead could be adapted for the spar (assuming all requirements could be met). Thus the focus of the SHm system development and assessment will be on the FS 626 Bulkhead Flange.

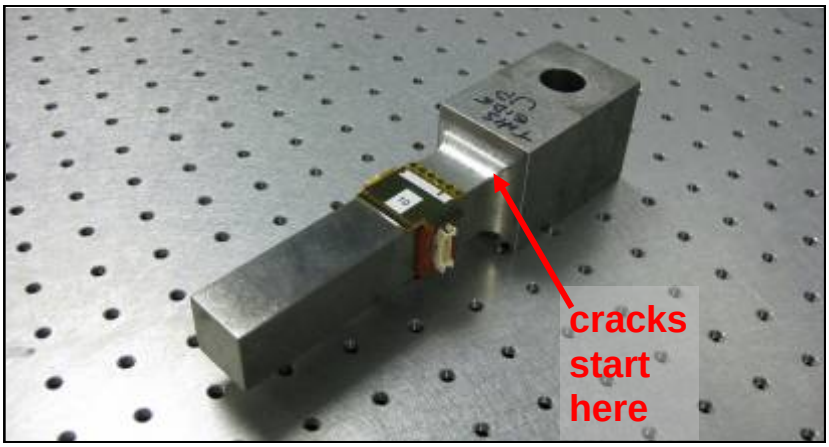
F.1.1 SHm Model Mature (Region Approach Verse Single Direction Approach) and Confidence

Piezoelectric-based ultrasonic systems are a reasonably mature technology. While not considered an off-the-shelf technology, Boeing has an extensive background with this technology. Current state-of-the-art assessments place this technology at a Technology Readiness Level in the range of 4 to 6 (depending upon the application, requirements, etc.).

The application-dependent nature of these systems drives non-standard device topologies. Rapid design and evaluation of these designs requires physics-based modeling tools for ultrasonic wave propagation in three-dimensions. These modeling tools are mature and are being used to develop solutions under the AFRL Hot Spot program.

F.1.2 Define What Type Of Data Will Be Available? Crack Found or Crack Size Information?

The data produced by the SHm system can vary based on need. Different damage indicators/parameters can be gathered from the same system depending upon what types of actuation signals are used and how the received data is processed. Figure F-1 shows a recent example using a piezoelectric receiving array to size a fillet crack in a Titanium cantilever specimen. As shown in the plot in the lower portion of the figure, several different damage indices were developed and calibrated to predict crack length.



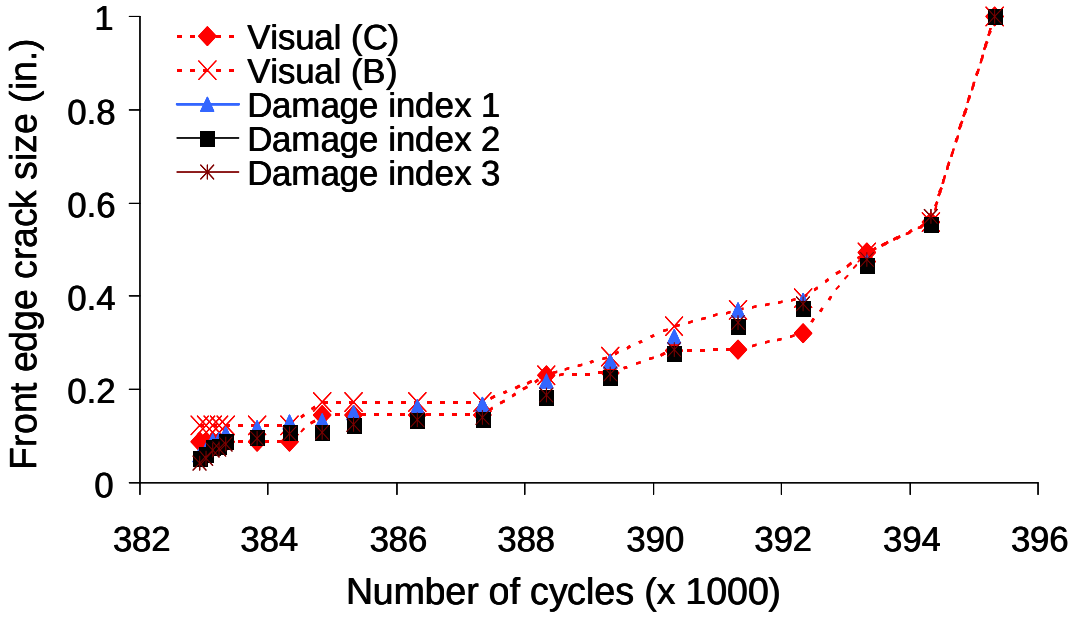


Figure F-1. Plot of Damage Indices versus Load Cycles

Data from piezoelectric ultrasonic arrays can be processed to form a variety of damage indices. Damage indices can be calibrated using experimental data (visual data in this example) as shown in the lower plot.

A critical element of this type of crack detection is the repeatability of the crack initiation location. For applications where the initiation site can vary, multiple algorithms are used to first help predict initiation, and then determine growth.

F.2 Hot Spot Project Impact Identified And Progress Report To Team

The Hot Spot program is currently developing the AFRL/Boeing SHm Design Framework in the context of metallic and composite crack detection implementation prototypes. A follow on activity has been negotiated to, in part, address the specific needs of F-15 (i.e., the 626 bulkhead). An internally funded Boeing effort has been on-going throughout 2009. Additional support from AFRL will begin in the fourth quarter of 2009 and combined AFRL/Boeing funded efforts are in place for 2010 and beyond.

Appendix G. ASIP Engineering Analysis Process

The purpose of this Appendix is to present the findings for Step 1 of the Sub-section 1.1.1.2 Architecture Prototype which was to evaluate the current ASIP engineering analysis process with special attention to any established risk assessment process. The following are items are the contents of this Appendix:

1. The overall ASIP engineering process is well defined as discussed in MIL-STD-1530C. For the proposed CBM+SI demonstration purpose, the engineering process of the ASIP's task 5, i.e., FSMP will be elaborated in more details and shown in section G.1.
2. To meet the CBM+SI requirements with predictive maintenance capability, the current FSMP process must consider risk assessment capability. Therefore, in addition to ASIP FSMP, the risk assessment engineering analysis process needs to be discussed. The following subjects of risk assessment task will be discussed and shown in section G.2.
   a. Risk assessment engineering analysis process.
   b. Input data required and how to define the uncertainties of these input variables. From EIFS, Fracture toughness, L/ESS, crack growth curve, Geometry factor, etc.
   c. How to interpret the results.

G.1. ASIP Engineering Process

The current ASIP Engineering Process will be used as a baseline to create an innovative CBM+SI architecture prototype. The overall ASIP engineering process contains five major tasks as shown in Figure G-1. Some of the key functions for each major task are listed in Figure G-2.

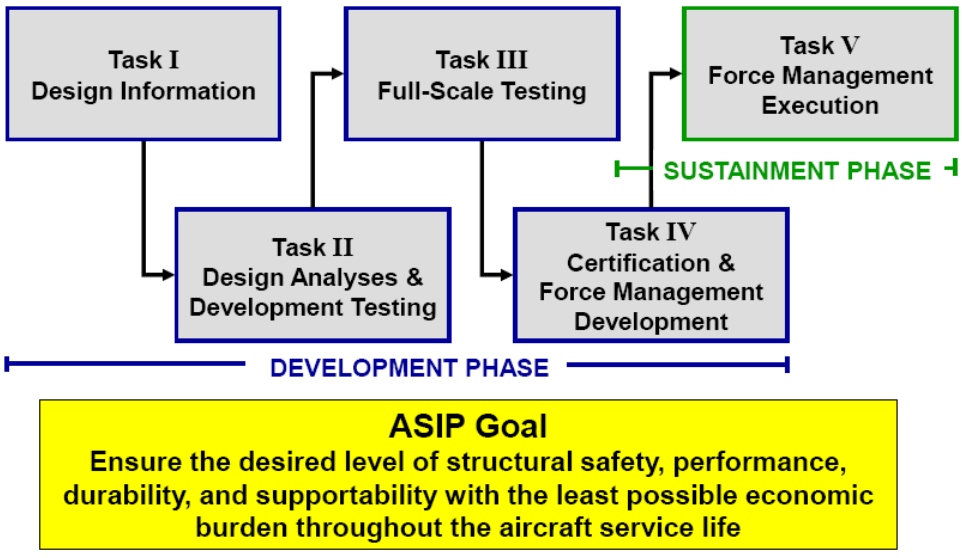


Figure G-1. ASIP Engineering Process

Task I	Task II	Task III	Task IV	Task V
Design Information	**Design Analyses & Development Tests**	**Full-Scale Testing**	**Certification & Force Management Development**	**Force Management Execution**
ASIP Master Plan Design Service Life and Design Usage Structural Design Criteria Durability & Damage Tolerance Control Program Corrosion Prevention and Control Program Nondestructive Inspection Program Selection of Materials, Processes, Joining Methods, & Structural Concepts	Materials And Joint Allowables Load Analyses Design Service Loads Spectra Design Chemical, Thermal & Environment Spectra Stress Analysis Damage Tolerance Analysis Durability Analysis Corrosion Assessment Sonic Fatigue, Vibration & Flutter Analyses Mass Properties Analysis Survivability Analysis Design Development Tests Initial Risk Analysis	Static Tests First Flight Verification Ground Tests Flight Tests Durability Tests Damage Tolerance Tests Climatic Tests Interpretation & Evaluation of Test Results	Certification Analyses Strength Summary & Operating Restrictions Force Structural Maintenance Plan Loads/ Environment Spectra Survey Development Individual Aircraft Tracking Program Development Rotorcraft Dynamic Component Tracking Program Development	Individual Aircraft Tracking Program Rotorcraft Dynamic Component Tracking Program Loads/Environment Spectra Survey ASIP Manual Aircraft Structural Records Force Management Updates Recertification

Figure G-2. Key Functions for Each Major ASIP Task

For the demonstration purpose, the proposed CBM+SI will be focused on the Task V of this engineering process. The following Figure G-3 contains the engineering analysis process for ASIP's Task V.

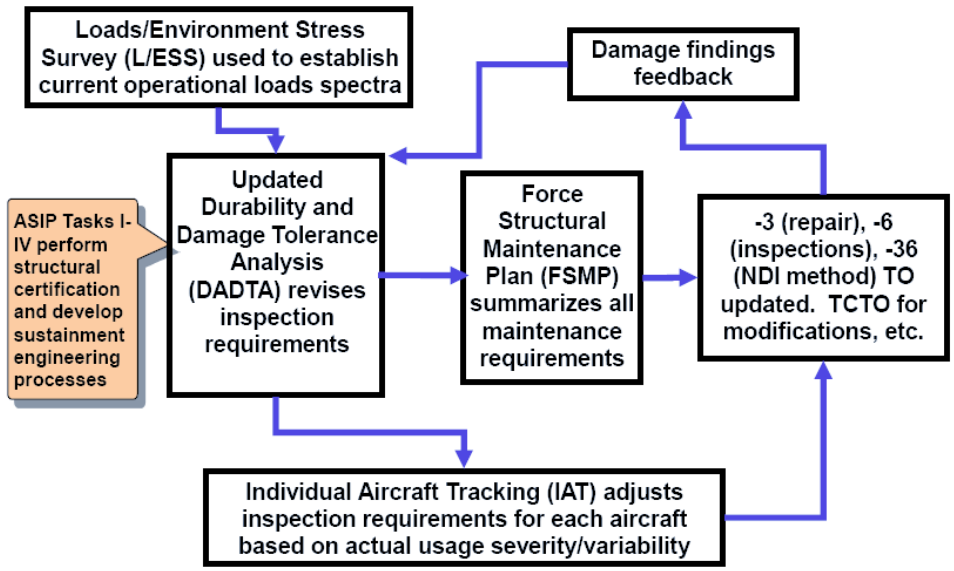


Figure G-3. ASIP Task V Engineering Analysis Process

As shown, the key elements of Task V contain key diagnostic capabilities (IATP and L/ESS) for ASIP to predict the inspection requirements for the FSMP plan. For the F-15 program, standard applications used at the Boeing company has accomplished this task through the use of a three-part individual aircraft tracking: (1) onboard flight data recorder, (2) ground support equipment for flight data recorder data retrieval and system maintenance (assumed to exist, but development/implementation could be undertaken), and (3) the Individual Aircraft Tracking

Program (IATP) consisting of a system of software applications and associated Oracle database hosted at a central data processing facility.

A Loads Environment Spectra Survey (L/ESS) and subsequent update of the Damage Tolerance Assessment (DTA) are performed by The Boeing Company. The instrumentation installed on every aircraft as part of the IATP is sufficient to construct load/stress time histories such that specially instrumented aircraft are not necessary to support a L/ESS program. Recorder data from all aircraft is routinely gathered and stored as part of the IATP. With data available on a continual basis, an L/ESS program becomes mainly an analytical exercise undertaken at any time. The L/ESS consists of an effort in which the archived recorder data is studied and average usage spectra for the DTA locations are generated. The fatigue lives of airframe locations analyzed in the Damage Tolerance Analysis are then re-estimated based on the latest in-service usage spectra and the Force Structural Maintenance Plan is updated.

G.2. ASIP Risk Assessment Engineering Process

For the proposed CBM+SI, the risk assessment engineering analysis process is required to predict an optimal maintenance schedule for the FSMP plan. To meet the requirement, the risk assessment engineering analysis process will be discussed and shown in Figure G-4. The input data requirements are shown in the left side block of Figure G-4. All data can be identified from the ASIP tasks. According to MIL-STD-1530C, three various stage of risk analyses need to be performed. For demonstration purposes, only the last task Section 5.5.6.3 will be performed here and most of the data comes from the FSMP task, e.g., IATP, L/ESS, and NDE etc.

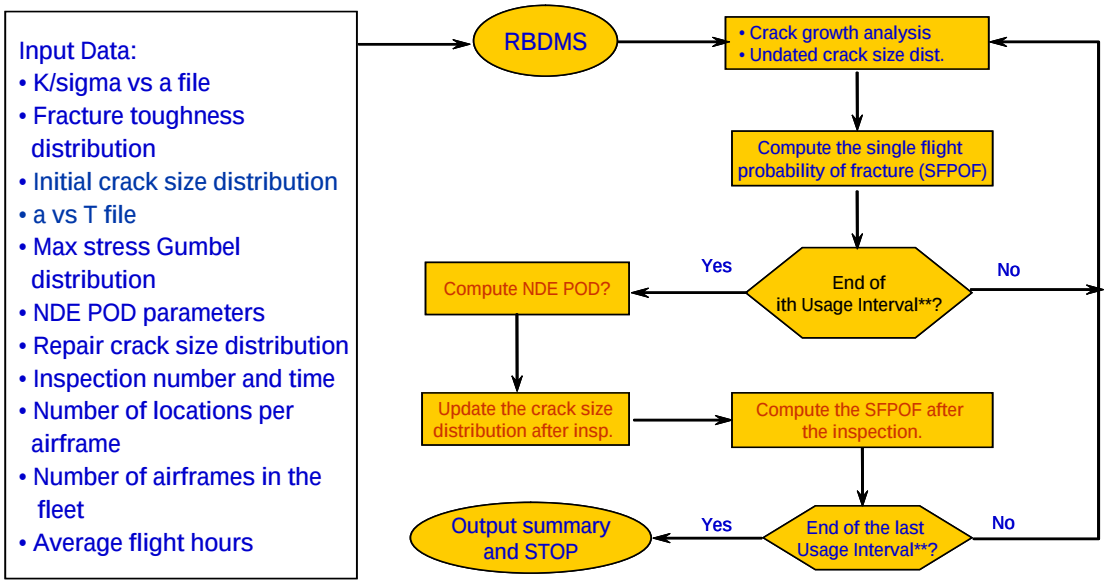


Figure G-4. Risk Assessment Analysis Process and Input Data Requirements

Input Data Requirements:

Current ASIP is ready to provide the basic required information to perform an effective risk assessment except for a probabilistic analysis strategy. These basic requirements are:

1. Aircraft usage characterization: L/ESS or IAT data
2. Crack growth and residual strength based on demonstrated usage and location of interest, material parameters, and stress intensity solution ($\alpha = K/\sigma$)
3. Inspection data: Crack size and usage hours at detection

With this data, a probabilistic risk assessment can be used to compute the risk and compare with the single flight probability of failure requirement stated in Mil-Std-1530C. With the proposed probabilistic risk assessment strategy, the safety factor associated with the existing deterministic approach can be "converted" into the risk and thus calibrated accordingly.

With a risk threshold requirement of 1.0E-7 defined within recently released Mil-Std-1530C, a comprehensive risk assessment process with consideration of both the PROF code and the Boeing in-house risk assessment code (RBDMS) for evaluating the future inspection schedule is required. The rationales for selecting the proposed comprehensive risk assessment process will be discussed and how to use the proposed comprehensive process for the future Force Structural Maintenance Plan is considered.

Uncertainties Modeling Strategy

Based on the proposed comprehensive risk assessment process, strategies for uncertainty modeling play an important role in estimating risk. Fracture toughness, Maximum stress, and initial crack size are key contributors to the risk estimation. In addition, the parameters required for the NDI's probability of detection curve and repair crack size distribution are key contributors for risk mitigation purpose.

In the following sub-sections, some general guidelines for uncertainty modeling of typical random variables, listed below, are developed.

1. Initial crack size distribution
2. Repair crack size distribution
3. Fracture toughness distribution
4. Maximum stress distribution
5. POD parameters

Initial Crack Size Distribution

The initial crack size distribution either comes from an equivalent initial flaw size characterization, or is inferred from the sizes of cracks that are detected during inspections of the critical location.

Without enough credible data, it is a very difficult task to model the initial crack size distribution. Thus, it is important to model the initial crack size distribution with two very common conservative assumptions from the traditional deterministic approach: a 0.05 inch crack with an associated 0.999999 probability of detection level and a 0.0025 inch crack at a 50% POD level. Based on these two assumptions, with proper selection of distribution types, several distributions can be modeled. The following two examples are modeled based on these two assumptions:

1. Weibull with shape parameter (al) = 0.998855 and scale parameter (be) = 0.00360825. For the Weibull distribution, the PROF code requires input data (be, al), to convert to mean and standard deviation.
    a. mean = be *gamma(1+1/al), gamma is a function.

b. std**2 = be^2 *(gamma(1+2/al)-gamma(1+1/al)^2)
c. pdf = alpha/beta*(x/beta)^(alpha-1)*exp(-(x/beta)^alpha)
d. cdf = 1- exp(-(x/beta)^alpha)
e. When al = 1, then the Weibull distribution becomes an exponential distribution
    i. cdf = 1 -exp(-(x/beta)) and failure rate = 1/beta
f. For the RBDMS code, the inputs are (al, be). Both parameters will then be converted into mean and standard deviation using the above functions.

2. Lognormal with mean = 2.955E-3 and standard deviation = 1.862E-3. For lognormal distribution, the following formula are critical to convert Lognormal into a standard normal distribution with mean = 0 and standard deviation = 1.
    a. COV = coefficient of variation = standard deviation/mean
    b. Median value of X = (mean value of X)/(1+COV^2)^0.5
    c. Mean value of normal Y (log X = Y) = log (median value of X)
    d. Standard deviation of normal Y = (log (1+cov^2))^0.5
    e. With mean and standard deviation of normal variable Y, the pdf and cdf of X can be calculated.

In addition, initial crack size distributions used in the PROF III code were considered. These distributions were derived form a teardown inspection results and backed out to create the initial crack size distributions:

1. Weibull (shape = 0.45, scale = 0.0000417)
2. Weibull(shape =0.5, scale = 0.0001534)
3. Weibull(shape =0.575, scale = 0.0002187).

The last distribution considered was used by earlier version of the PROF code and it is a Lognormal and Uniform mixed distribution – Lognormal (mean = 9.455E-4 and standard deviation = 5.95744E-4) with 99.9% and Uniform (lower bound = 0 and upper bound = 0.05) with 0.1%.

All of the above distributions were plotted in Figures G-5 and G-6. As shown, distributions with larger crack sizes will produced higher risk, e.g. Lognormal (2.955E-3, 1.862E-3) and Log and Uniform mixed. The distributions with smaller crack sizes will have smaller risk, e.g., Weibull (0.45, 0.0000417) and Weibull (0.5, 0.0001534). For conservatism, the user may consider initial crack size distribution that will cause highest risk and that is Weibull (0.998855, 0.00360825).

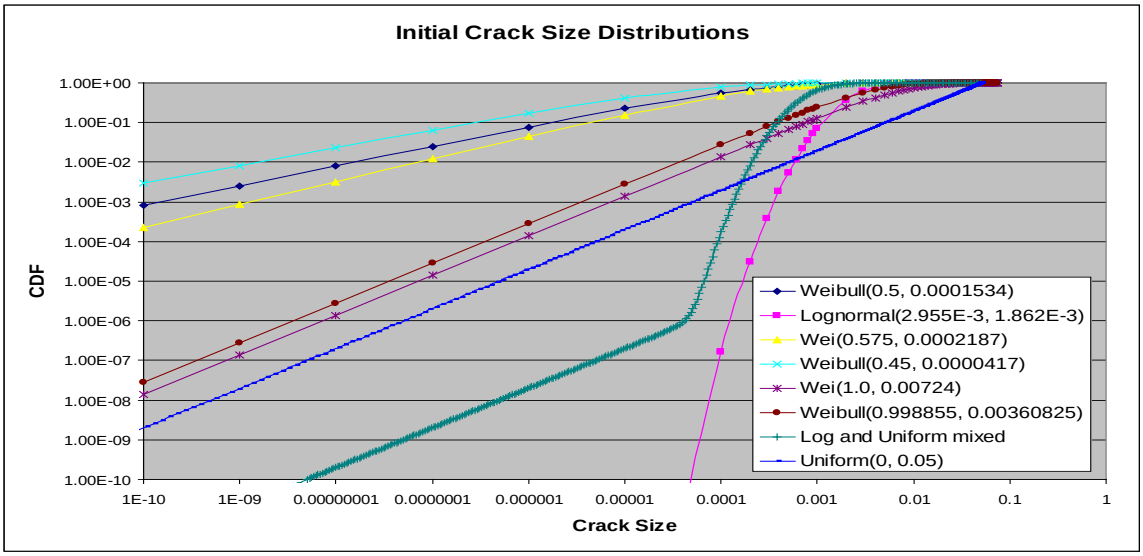


Figure G-5. Various Initial Crack Size Distribution (Log-Log)

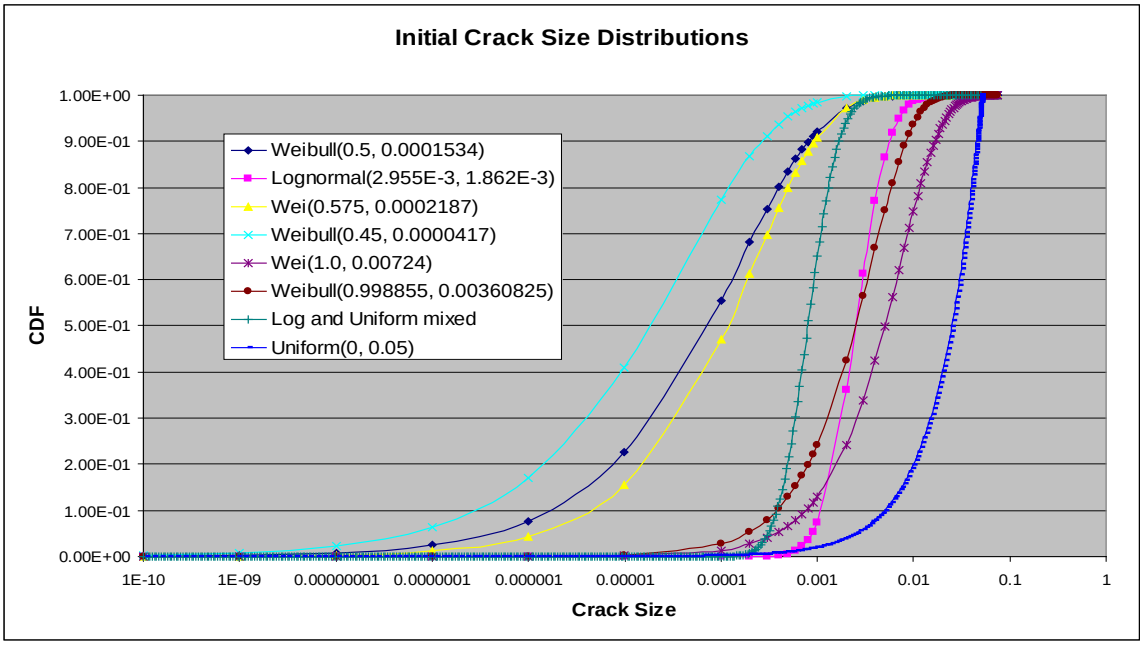


Figure G-6. Various Initial Crack Size Distribution (Normal-Log)

Repair Crack Size Distribution

Since the Eddy Current inspection technique was used to find the cracks, it is reasonable to assume 0.05" as the repaired initial crack size. Given the same 0.05", the uniform distribution with lower and upper bounds of 0.0 and 0.05 should be a reasonable distribution to model the repair crack size distribution. For a Uniform distribution, the following properties are important:

- mean = (upper +lower)/2.
- Std dev. = ((upper – lower)^2 / 12.)^0.5

In addition, repair crack size distributions used in the PROF code were considered. Exponential distribution was used by the PROF code to model the repair crack size distribution. Exponential is a special case of the Weibull distribution when the shape parameter = 1. In the following, three Exponential distributions were defined based on different CDF values given the crack size of 0.05.

1. Weibull(shape = 1.0, scale = 0.00723842), CDF(0.05) = 0.999
2. Weibull(shape = 1.0, scale = 0.00542868), CDF(0.05) = 0.9999
3. Weibull(shape = 1.0, scale = 0.00434294). CDF(0.05) = 0.99999

The Weibull (1.0, 0.00723842) and Uniform (0, 0.5) distributions were also plotted in Figures G-5 and G-6. Note that when using the Weibull distribution, there are some populations well above the 0.05 crack size limit.

Fracture Toughness (Kc) Normal Distribution

To determine the parameters of a strength variable, it usually can be done by using the strength variable's A-basis (above the value has 99% population with 95% confidence) and B-basis (above the value has 90% population with 95% confidence) values. From both data, with an assumption of the number of samples, the mean and standard deviation of this distribution can be back calculated. However, for the fracture toughness, the above information was not available. Because of extra conservatism added in the safety factor (usually > 2) for fatigue failure mode, there was no extra effort to perform additional tests to determine the A-bassis or B-basis values.

Without actual data, a normal distribution with the coefficient of variation (μ/σ) from about 3% to 10% for aluminum and titanium alloys, and most steels was used to model the Kc distribution. Therefore, for these materials, in the absence of data, the standard deviation will be estimated by a multiple between 3 and 5 percent of the mean Kc. If a constant Kc is desired for the analysis, the standard deviation could be set as a very small number. For a more conservative assessment, the standard deviation will be estimated by a multiple between 6 and 10 percent of the mean Kc. A simple sensitivity analysis can be performed to determine the value. In the following Table G-1, the fracture toughness variables used for all nine fatigue critical locations are summarized:

Table G-1. Fracture Toughness Variables

FCL Names	Mean	Standard Deviation	Coefficient of Variation
AIF18	68.00	3.20	4.71%
HS-6U	205.60	7.80	3.79%
W2	33.00	2.20	6.67%
W16	34.00	2.20	6.47%
W27	38.00	2.20	5.79%
W33	27.00	2.20	8.15%
WCT6b	70.00	3.20	4.57%
WCT12	205.60	7.80	3.79%
WCT61	205.60	7.80	3.79%
		Average	5.30%
		Standard deviation	1.55%

As shown the average value of all 9 COVs = 5.3% and standard deviation of all 9 COVs = 1.55%. Thus, a COV of 10% is considered an upper bound which is about 3 sigma value. Note that the higher COV will produce a higher risk estimate.

Maximum Stress Gumbel Distribution

The distribution of this maximum stress peak per flight is modeled in terms of a Gumbel distribution of extreme values. For practical purposes, it can be assumed that the stress peak that will cause fracture is the largest peak to be encountered in a flight. Since available data might not extend to the largest stresses that might be encountered, a consistent basis for extrapolation was required. The following discussion presents the rationale for this choice and a method for estimating the parameters of the model. Note that the same modeling strategy for the maximum stress was also applied by the PROF code but the RBDMS code will select a slightly different stress distribution.

In an operational flight, the number and magnitude of the experienced stress peaks are random variables both of which are influenced by the mission being performed. Let $F_{all}(\sigma)$ represent the cumulative distribution function of the magnitude of all stress peaks greater than a threshold for the stratification of the operation being modeled. Let $H(\sigma)$ represent the cumulative distribution function of the maximum stress encountered in a flight. If a flight consists of n stress cycles selected at random from the population described by $F_{all}(\sigma)$ and if σ_{max} represents the largest peak in a flight, then a max

$$H(\sigma) = P(\sigma_{max} < \sigma) ,$$

$$= P(\text{all n peaks} < \sigma)$$

$$= [F_{all}(\sigma)]^n$$

Gumbel showed that for exponential type distributions with large n, the above equation can be approximated by

$$H(\sigma) = \exp\{-\exp[-(\sigma-Bsig)/Asig]\} , \text{ where}$$

- mean value= bsig + 0.577*asig
- standard deviation = (1.283*asig)

Flights that contain large stress peaks are usually very active and also contain a large number of peaks. Therefore, this asymptotic relation was incorporated as the model for extrapolating and describing the distribution of the maximum stress per flight. The parameters of this Gumbel distribution can be estimated as follows.

First, the cumulative distribution of the maximum stress per flight is estimated from data. Peak stress data will be available as flight-by-flight stress sequences or exceedance curves for the expected usage at the analysis location. If a flight-by-flight stress history is available, the maximum stress in each flight can be extracted and the cumulative distribution function of these maximum stresses per flight is calculated directly as:

$$H(\sigma_i) = n_i / N$$

where n_i is the number of stress maxima less than σ_i and N_i is the total number of flights. If only an exceedance curve is available for describing the magnitude of the expected stresses, the exceedance curve must first be converted to the distribution function, $F_{all}(\sigma)$.

$$F_{all}(\sigma i) = 1 - \lambda(\sigma_i) / \lambda(\sigma_{thr})$$

where $\lambda(\sigma_i)$ is the number of peak stresses per unit time exceeding σ_i and $\lambda(\sigma_{thr})$ is the number of exceedances per unit time of the stress threshold. Let n_{bar} represent the average number of stress peaks per flight greater than threshold.

$$n_{bar} = (\text{\# of peaks in spectrum}) / (\text{\# of flights in spectrum})$$

Then the cumulative distribution of the maximum stress per flight is estimated by the following function:

$$F_{max}(\sigma_i) = [1 - \lambda(\sigma_i) / \lambda(\sigma_{thr})] \wedge n_{ba}$$

Next note that $H(\sigma_i)$ can be transformed to

$$\ln\{-\ln[H(\sigma_i)]\} = -\sigma_i / Asig + Bsig / Asig$$

A least squares fit of the (σ_i, $\ln\{-\ln[H(\sigma_i)]\}$) data pairs will yield estimates of -l/Asig and Bsig/Asig. To ensure that the fit is acceptable at the high stress levels of most influence in the hazard computation, only the highest stress ranges in the data should be used in determining the least squares fit. It might be noted that Bsig is the stress that is exceeded in 63 percent of the flights and Asig is proportional to the steepness of the exceedance probability versus stress curve. The larger the value of Asig, the flatter the exceedance probability curve (resulting in a larger probability of large maximum stress peaks in a flight). A practical approach to estimating Asig and Bsig is to vary these parameters until an acceptable fit is obtained for the probability of exceeding the high stress levels which drive the risk calculations of practical interest. Engineering judgment is required when selecting the appropriate fit. It is easily possible to have a large estimate of Asig that can result in a positive probability of encountering a practically impossible stress.

The maximum stress per flight input comprises the two parameters Asig and Bsig of the Gumbel asymptotic distribution for maxima of exponential type distributions. The fit was obtained from the table of stresses that represented 225 flights with an average number, n_{bar}, of 100 cycles per flight. Only the highest stress levels are included in the table of Figure G-7. The complete exceedance table included a total of 22587 stress peaks.

Sigma MAX	No. of Cycles	Peak CDF (1-(Column B/22587.52)	Observed CDF max/flight Column C^(22587.52/100)	Gumbel Transform LN(-LN(Column D)	1-Column D	8 point calculated EXP(-EXP(-(sigma-B)/A))	Prob of exceeding 1- (8 point calculated)
6.85	22587.52	0.0000	0.0000		1.0000	0.0000	1.0000
9.01	13326.55	0.4100	0.0000	5.3052	1.0000	0.0000	1.0000
10.04	7862.61	0.6519	0.0000	4.5710	1.0000	0.0000	1.0000
10.70	4638.91	0.7946	0.0000	3.9498	1.0000	0.0000	1.0000
11.27	2736.94	0.8788	0.0000	3.3733	1.0000	0.0000	1.0000
11.81	1614.78	0.9285	0.0000	2.8186	1.0000	0.0000	1.0000
12.32	952.71	0.9578	0.0001	2.2756	0.9999	0.0000	1.0000
12.82	562.10	0.9751	0.0034	1.7391	0.9966	0.0000	1.0000
13.32	331.64	0.9853	0.0354	1.2063	0.9646	0.0015	0.9985
13.81	195.66	0.9913	0.1401	0.6756	0.8599	0.0526	0.9474
14.24	115.44	0.9949	0.3143	0.1461	0.6857	0.2301	0.7699
14.58	68.11	0.9970	0.5055	-0.3825	0.4945	0.4283	0.5717
14.93	40.18	0.9982	0.6689	-0.9109	0.3311	0.6179	0.3821
15.32	23.71	0.9990	0.7888	-1.4387	0.2112	0.7740	0.2260
15.77	13.99	0.9994	0.8694	-1.9665	0.1306	0.8836	0.1164
16.19	8.25	0.9996	0.9208	-2.4948	0.0792	0.9392	0.0608
16.44	4.87	0.9998	0.9525	-3.0220	0.0475	0.9590	0.0410
16.69	2.87	0.9999	0.9717	-3.5508	0.0283	0.9724	0.0276
16.94	1.69	0.9999	0.9832	-4.0804	0.0168	0.9815	0.0185
17.19	1.00	1.0000	0.9900	-4.6051	0.0100	0.9876	0.0124

Figure G-7. W-2 Location – Gumbel Distribution Modeling

The fit of the Gumbel distribution using the top five and top eight stress values of the spectrum is presented in Figure G-8. Using lower stress values may provide a better fit at the lower levels at the expense of a poorer fit at the largest levels. The highest stress levels are the only ones of importance in the hazard calculations. The model tends to predict higher probability of occurrences for the smaller stress peaks. Depending on the source of the exceedances or stress cycles per flight data, the max stress per flight data to be fit are likely to represent a mixture of mission types. They are not a random sample from a single population. The maximum stresses from the flights of less severe mission types would not be as large, and they bias the distribution of maximum stresses per flight to be fit. By restricting the Gumbel fit to the high stress ranges, this bias is avoided at the expense of a slightly more conservative estimate of the risk.

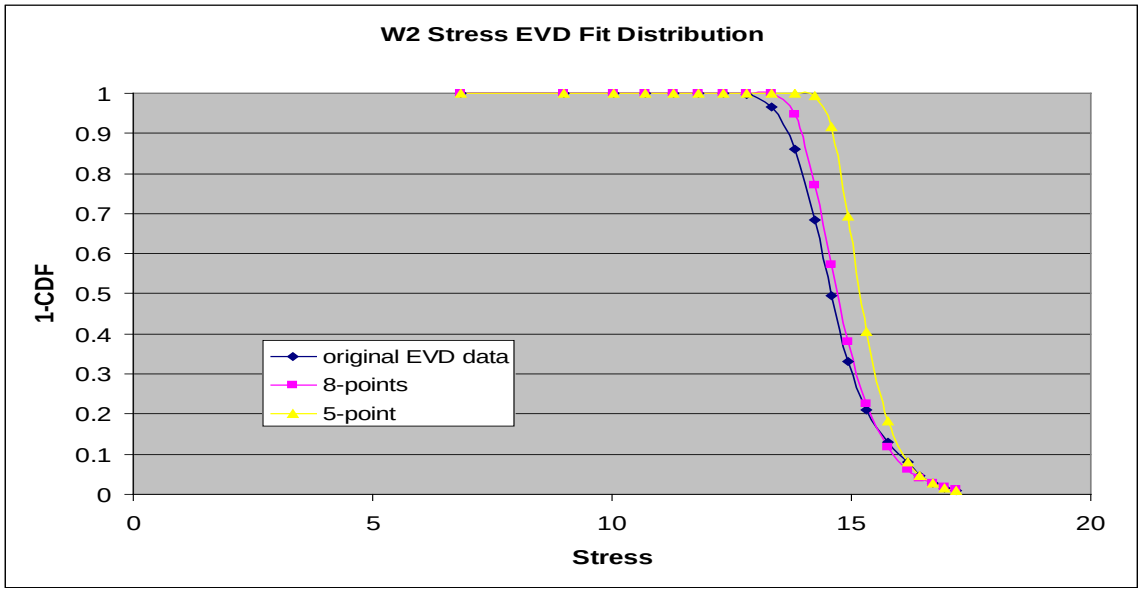


Figure G-8. W-2 Location Fit to Distribution of Maximum Stress per Flight

Based on load exceedance curve, the maximum stress's Expected Value Distribution can be modeled. Since the largest loads will produce higher risk, the fitted distribution will consider the largest few points (5 or 8). As shown in Table G-2, 5 points fit produced much smaller COV than the 8 points fit. Based on these data, all nine fatigue critical locations were run and found that 8 points fit produced much better fit and more conservative results, i.e., higher risk. Therefore, 8-points fit maximum stress distribution is chosen for the proposed risk assessment process.

Table G-2. Comparison of 5 and 8-points fit results

	5 points			8 points		
FCL Names	Mean	Standard Deviation	COV	Mean	Standard Deviation	COV
AIF18	18.00	0.43	0.024	17.30	0.73	0.042
HS-6U	14.21	1.04	0.073	14.22	0.96	0.067
W2	15.28	0.61	0.040	14.83	0.79	0.053
W16	14.31	0.81	0.056	14.16	0.87	0.061
W27	18.00	0.43	0.024	17.30	0.73	0.042
W33	10.90	0.38	0.035	10.65	0.49	0.046

WCT6b	**15.41**	**0.47**	**0.030**	**14.62**	**0.73**	**0.050**
WCT12	**43.97**	**1.28**	**0.029**	**42.59**	**1.88**	**0.044**
WCT61	**27.96**	**1.05**	**0.038**	**27.05**	**1.44**	**0.053**

Probability Of Detection (POD) Parameters

A new lognormal POD model was developed to replace the approximate POD curve (approximate to lognormal) as shown below:

$$POD(a) = \left[1 + \exp\left(-\frac{\pi}{3}\left(\frac{\ln(a - a_{\min}) - \mu}{\sigma}\right)\right)\right]$$

Based on Lognormal variable X, the following parameters need to be determined:

- median value of X = mean value of X /(1+COV^2)^.5
- mean value of (log X = Y) = log (median value of X)
- standard deviation of (Y)=(log(1+COV^2))^.5

To model the probabilities of detection (POD) curves, the crack size that can be detected with 90% detection and 95% confidence level must first be identified. Assumed the eddy current inspection method, 0.075 inches is the 90% detection and 95% confidence level. The input parameters for the lognormal POD are amed (median value of X), asteep, amin (minimum value of X), and Probability Of Inspection (POI). To identify these parameters for 0.075 inches case, the following function is used:

- pod(a) = standard normal((dlog(a-amin)-dlog(amed))/asteep) * POI
    - pod(0.075) = 0.9 = standard normal((dlog(a-amin)-dlog(amed))/asteep) * POI
    - pod(amed) = 0.5 = standard normal((dlog(amed-amin)-dlog(amed))/asteep) * POI

Assume POI = 1.0, then

- 0.9 = standard normal [Log (0.075)-log(amed)]/asteep] = Φ [Log (0.075)-log(amed)]/asteep]
- Φ^{-1} (0.9) = 1.28 = [Log (0.075)-log(amed)]/asteep

- Additional point at median value, then,
    - Standard normal (0.5) = 0 = [Log (a)-log(amed)]/asteep

For amed = 0.06 case, based on the above functions, asteep can be calculated as 0.1743. In the following Table G-3, various amed are assumed to calculate its corresponding asteep.

Table G-3. Lognormal POD Parameters Example

amed =	asteep =	90% POD a =	50% POD a =	10% POD a =
0.0600	0.1743	0.0750	0.0600	0.0480
0.0500	0.3168	0.0750	0.0500	0.0333
0.0400	0.4911	0.0750	0.0400	0.0213
0.0300	0.7159	0.0750	0.0300	0.0120
0.0200	1.0326	0.0750	0.0200	0.0053
0.0100	1.5741	0.0750	0.0100	0.0013

As for the amin and POI, usually amin = 1.0E-20 and POI = 1.0. Sensitivity study can be done to study the impact of these two parameters in the future.

Important Deterministic Input Data

Crack Growth Curve (Crack Size a (inches) vs. Flight Hours T) – the same deterministic DTA results will be used to perform the growth of fatigue cracks by projecting the percentiles of the fatigue crack size distribution. After inspection, detected cracks will be repaired and the crack size distribution will be updated with undetected cracks and repaired cracks. The proportion of cracks that is detected and repaired depends on the POD(a) function of the selected NDI system.

Geometry (Crack Size a (inches) vs. K/sigma) – Under current USAF regulations, damage tolerance analyses are performed for every critical location on an airframe. As part of these analyses, the stress intensity factor geometry correction, $\beta(a)$, for correlating stress, loading condition, global geometry, and crack size will have been determined. The geometry file also plays an important role when computing the risk as shown in the following limit state function:

$$g = K_C / \left[\sqrt{\pi a}\,\beta(a)\right] - \sigma_{\max}$$

For interval probability of failure, the following data are important:

- Similar locations in an aircraft
- No. of aircraft in a fleet
- Average hours per flight

How to interpret the results

The calculated single flight probability of failure (or hazard rate) should be used to compare with the following limits.

1. A probability of catastrophic failure at or below 10^{-7} per flight for the aircraft structure is considered adequate to ensure safety for long-term military operations.
2. Probabilities of catastrophic failure exceeding 10^{-5} per flight for the aircraft structure should be considered unacceptable.
3. When the probability of failure is between these two limits, consideration should be given to mitigation of risk through inspection, repair, operational restrictions, modification, or replacement.

Appendix H. CBM+ 10 Technologies and Concepts Definitions and Analysis Process

H.1 CBM+ 10 Technologies and Concepts Definitions

1. Prognostics is defined as, "the capability to provide early detection and isolation of precursor and/or incipient fault condition to a component or sub-element failure condition, and to have the technology and means to manage and predict the progression of this fault condition to component failure." The aforementioned characteristics are key in meeting the goal set forth in the DoD Interim Policy on CBM+. The goal is to perform maintenance only upon evidence of need. This is done, in part, through the use of embedding these prognostic capabilities within specific parts on the aircraft.

Within the CBM+ concept, data gathered from embedded prognostics can be downloaded and interpreted via a Portable Maintenance Aid (PMA). The PMA feeds information about insipient failures to decision-makers.

2. Diagnostics is "the process of identifying the cause of a malfunction (fault), by observing its effects at various monitoring (test) points in a system." This technology also plays a significant role in meeting the goal of CBM+; embedding advanced diagnostics capable of identifying specific faults within the aircraft and then having the fault data directly relayed to the PMA and to the maintainer.

On-board diagnostic information is downloaded via PMA or Interactive Electronic Technical Manuals (IETM). The diagnostics do a lot of the troubleshooting so the technician can focus on the repair.

3. Portable Maintenance Aids (PMAs) are mobile computing devices used at the point of maintenance. They act as the primary interface between the mechanic and on-board diagnostics and prognostics. "These devices are often used for technical data display, diagnostic fault isolation, repair mentoring, materiel management, maintenance documentation, health monitoring, prognostics, and operational data upload/download." In addition, PMAs on future aircraft will allow the maintainer to interact with the logistics chain for parts availability/supportability. Most PMAs in the future will interface with integrated information systems.

4. Interactive Electronic Technical Manuals (IETMs) tailor technical information into instructions for a specific repair under a specific set of input conditions. The instructions adapt to the technicians inputs about his/her observations. The interactive nature of the IETM provides diagnostic interpretation for legacy aircraft as well as computer-based training at the job-site. This gives the maintainer the correct instructions for the task at hand when needed. All of these capabilities are enablers of the CBM+ concept.

Note: It is important to mention that within the DoD we have numerous classes (types) of IETMs. Some IETMs are very basic and only have the ability to reproduce electronically indexed page images while other IETMs have advanced abilities, which include diagnostic interpretation, and interactive training capabilities found in PMAs.

5. Interactive Training PMAs and IETMs are used to conduct training at the aircraft within a CBM+ environment. This ability provides a better-informed, better-equipped maintainer ready to perform the required maintenance when called upon.

6. Data Analysis entails the failure rate (or probability) determination for basic events from available sources of failure information and knowledge." In the CBM+ context, data analysis is an assimilation of real-time and historical data into information usable for decision making. The data stored is within a common integrated information system accessible to all maintenance personnel. Armed with this information, we enhance our knowledge of parts/system performance, which, in-turn, increases system reliability. The combination of real-time and historical data provides the maintainer with maintenance management tools for predicting fleet health.

7. Integrated Information Systems are a "seamless composite of logistics functions and capabilities, accessible to any valid user at any time via an enterprise-wide architecture framework chartered to provide integrated solutions to meet the logistics community's operations needs. This includes modernizing and transitioning logistics information systems from legacy stovepipes to a fully integrated and compliant logistics systems environment." For future weapon systems, the aforementioned PMA will send maintenance data to integrated information system. The information will be used for a multitude of functions such as data analysis, parts availability, and automatic identification of parts.

An example of this technology is the Enterprise Data Warehouse (EDW). By integrating logistical data into one source, we provide a single source for all combat support, to include analytical and historical information. The Integrated Information System is a technology that enables improved maintenance and logistics practices.

8. Automatic Identification Technology (AIT) is defined within the DoD as the "proper mix of technologies that allow each user to efficiently and effectively capture, aggregate, and transfer data and information, and, as a consequence, integrate with Automated Information Systems (AISs) using the optimum technology for their particular application." What this means is cradle-to-grave tracking throughout the Air Force logistics systems of repairables, selected consumables, engines, equipment and other designated property to provide asset and item information and status.

9. Reliability-Centered Maintenance (RCM): "The definition of RCM is a disciplined, structured process to identify cost effective and technically sound maintenance policies. These policies could affect field or depot maintenance, supply, training, engineering, operator procedures, and technical data." Through the careful application of inspection and scheduled maintenance requirements, critical failures that can be anticipated will be minimized resulting in the highest probability of warfighting capability for legacy and future aircraft.

10. Joint Total Asset Visibility (JTAV) is "the capability to provide users with timely and accurate information on the location, movement, status, and identity of units, personnel, equipment and supplies. It also facilitates the capability to act upon that information to improve overall performance of DoD's logistics practices." The JTAV concept improves supply/maintenance planning and responsiveness, thereby increasing operational availability, improving maintenance and logistics practices. Within CBM+ a maintainer would change a part

only upon evidence of need. To delay any down time for that aircraft the maintainer would have to know when he would receive that part. JTAV allows the maintainer to do just that.

H.2 CBM+ Engineering Analysis Process

Engineering Analysis Process for the CBM+ 10 Key Technologies and Concepts are shown in Figure H-1. In the following, the analysis process for each key technology will be discussed in details and their relationship with the other key technologies will also be discussed.

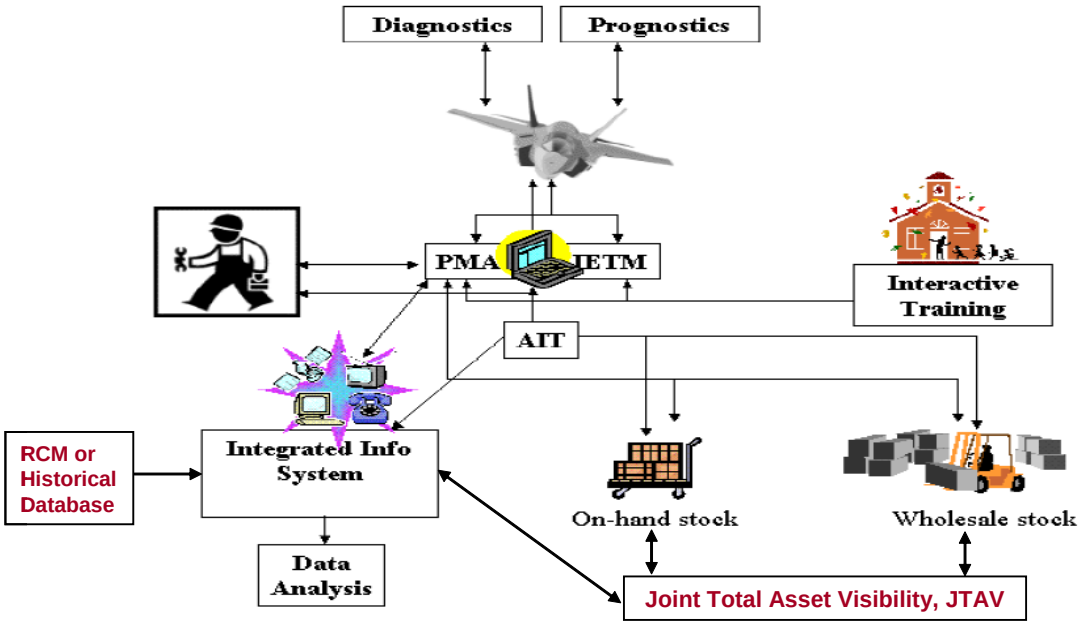


Figure H-1. Engineering Analysis Process for the CBM+ 10 Key Technologies and Concepts

1. On-board diagnostic information is downloaded via PMA or IETM. From Aircraft the process of identifying the cause of a malfunction (fault), by observing its effects at various monitoring (test) points in a system.
    a. ASIP process related: IATP, L/ESS
    b. Link with PMA or IETM
2. Through the use of embedding prognostic capabilities within specific parts on the aircraft, data gathered from embedded prognostics can be downloaded and interpreted via a PMA. Then, the data will be analyzed and determine when to perform maintenance only upon the evidence of need.
    a. Proposed Prognostic capability – SHm
    b. Link with PMA
3. PMA- These devices are often used for technical data display, diagnostic fault isolation, repair mentoring, materiel management, maintenance documentation, health monitoring, prognostics, and operational data upload/download.
    a. This module will link with maintainer, aircraft diagnostic capability, aircraft prognostic capability, JTAV, IETM, AIT, Interactive Training, and Integrated Information System.

b. Key data flow is to transfer Diagnostic and Prognostic data into IIS and data analysis module to perform analysis using both data sources and historical database from RCM or other database.

4. IETM – tailor technical information into instructions for a specific repair under a specific set of input conditions. The instructions adapt to the technicians inputs about his/her observations.
    a. Sometime works like a PMA
5. AIT - proper mix of technologies that allow each user to efficiently and effectively capture, aggregate, and transfer data and information, and, as a consequence, integrate with Automated Information Systems (AISs) using the optimum technology for their particular application.
    a. Integrated with PMA, IIS and maintainer
6. Interactive Training - This ability provides a better-informed, better-equipped maintainer ready to perform the required maintenance when called upon.
    a. Link with Maintainer through PMA or IETM.
7. Integrated Information System - the aforementioned PMA will send maintenance data to integrated information system. The information will be used for a multitude of functions such as data analysis, parts availability, and automatic identification of parts.
    a. Link with PMA or IETM to get real time data
    b. Link with RCM or historical database to get historical data
    c. Link with JTAV to get logistic information
    d. Link with Data Analysis to perform analysis
8. Data Analysis: data analysis is an assimilation of real-time and historical data into information usable for decision making
    a. Link with IIS with data from real time data (Diagnostic and Prognostic through PMA) and historical data (RCM or other database) to perform data analysis
    b. This capability should be link with risk based analysis tool to determine the optimal maintenance schedule.
9. RCM - Through the careful application of inspection and scheduled maintenance requirements, critical failures that can be anticipated will be minimized resulting in the highest probability of warfighting capability for legacy and future aircraft
    a. For this one, traditional RCM data will be used as a reference to support TPM analysis; however, to determine the optimal maintenance schedule, RCM should be replaced by Risk Based Approach.
    b. Link with IIS to store the real time data
    c. For TLCSM and TPM, the required data must be stored carefully and they are:
        i. Fleet Availability or Aircraft Availability Rate: This describes the readiness of the fleet by a percentage considered available for missions and not in any maintenance.
        ii. Total Cost of Ownership: This is the total cost to own and maintain the platforms and weapons systems from cradle to grave. For the CBM+SI evaluation, the period will cover from first year of research and

development to the last use of the fleet. Other ways to express this TPM include Return on Investment, Net Present Value, and Cash Flow.

iii. Maintenance Hours per Flight Hour: This is the average maintenance labor hours per flight hour. Another way to view the use of resources during operation is Resource Utilization.

d. For Structural Integrity program, FSMP is used to replace RCM; however, the concept of RCM should be applied. The failure modes identification is very similar to FSMP's focus on the control points of ASIP program. All the maintenance actions and results plus the aircraft usage data (IATP, L/ESS) have been recorded to make the decision for the next maintenance action.

i. RCM is discussed in the F-15 Force Structural Maintenance Plan (FSMP). The application of RCM on the F-15 program has been established as part of the Damage Tolerance Assessment (DTA). One key element of DTA and RCM is the definition of inspection intervals for critical airframe structure. These intervals are determined using fatigue crack growth analysis and actual usage fatigue spectra. The RCM inspection worksheets are periodically updated to incorporate in-service fatigue findings.

10. JTAV - The JTAV concept improves supply/maintenance planning and responsiveness, thereby increasing operational availability, improving maintenance and logistics practices. Within CBM+ a maintainer would change a part only upon evidence of need. To delay any down time for that aircraft the maintainer would have to know when he would receive that part.

a. Link with IIS and AIT

Appendix I. CBM+SI Architecture

I.1 Step 3 CBM+SI Architecture Prototype

The main objective of this task is to develop an integrated, predictive maintenance CBM+SI architecture prototype for an identified F-15 platform structural component, the bulkhead failure mode of F-15. This architecture must have the following capabilities:

- Developing integrated, predictive maintenance approaches, which minimize unscheduled repairs, eliminate unnecessary maintenance, and employ the most cost-effective maintenance health management approaches.
- Determining an optimum mix of maintenance technologies.
- Identifying the optimum opportunity to perform required maintenance.
- Providing real-time maintenance information and accurate technical data to technicians and logisticians.

As discussed in step 1 of this Architecture subtask, after review of ASIP engineering analysis process, only the ASIP's Task V, FSMP's engineering analysis process was required for the demonstration and shown in Figure I-1.

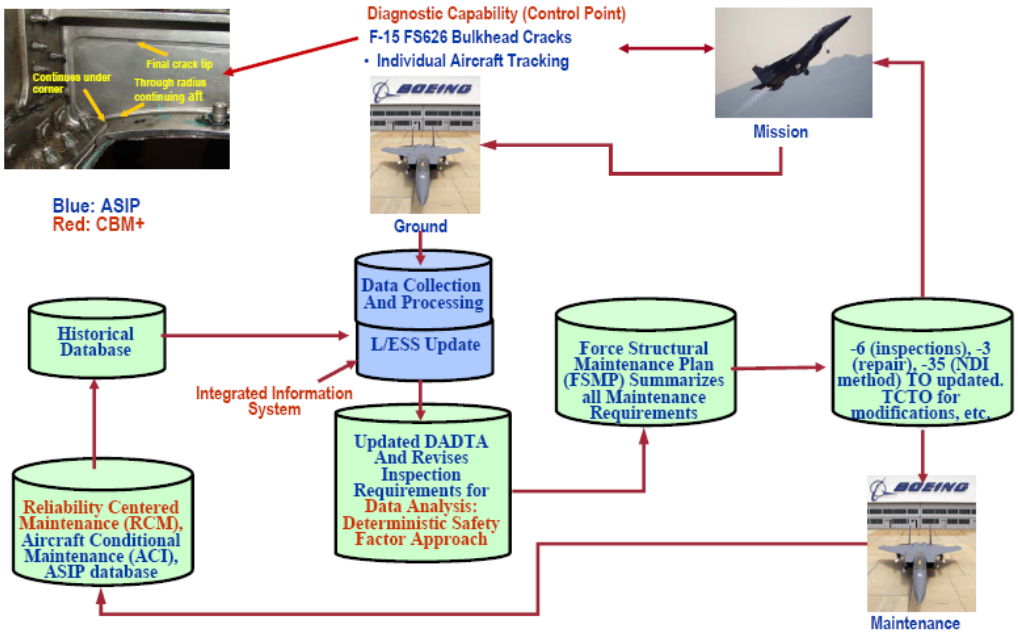


Figure I-1. ASIP Architecture for the Demonstration Example

In Figure I-1, key FSMP's capabilities are included:

1. IATP and L/ESS for Diagnostic purpose: Data collection and processing
2. Updated Durability and Damage Tolerance Analysis (DADTA): based on collected data (or usage data), the updated DADTA data will be calculated with consideration of the safety factor to determine the updated inspection intervals.
3. FSMP: from the updated DADTA and a deterministic safety factor, FSMP plan for all the control points will be updated and executed.

4. NDI inspection and repair: Based on FSMP plan, critical locations (or control points) were inspected and repaired accordingly.
5. Maintenance data collection: similar to Reliability Centered Maintenance (RCM) concept, all the maintenance data will be collected for future updates. These data can also be used to select the most severe failure locations for further updates.

All of the above technologies are required for the selected demonstration example. For comparison purpose, based on the same kind of framework, the proposed 10 CBM+ technologies and concepts, as discussed in Step 2 of this subtask, can be applied and shown in Figure I-2.

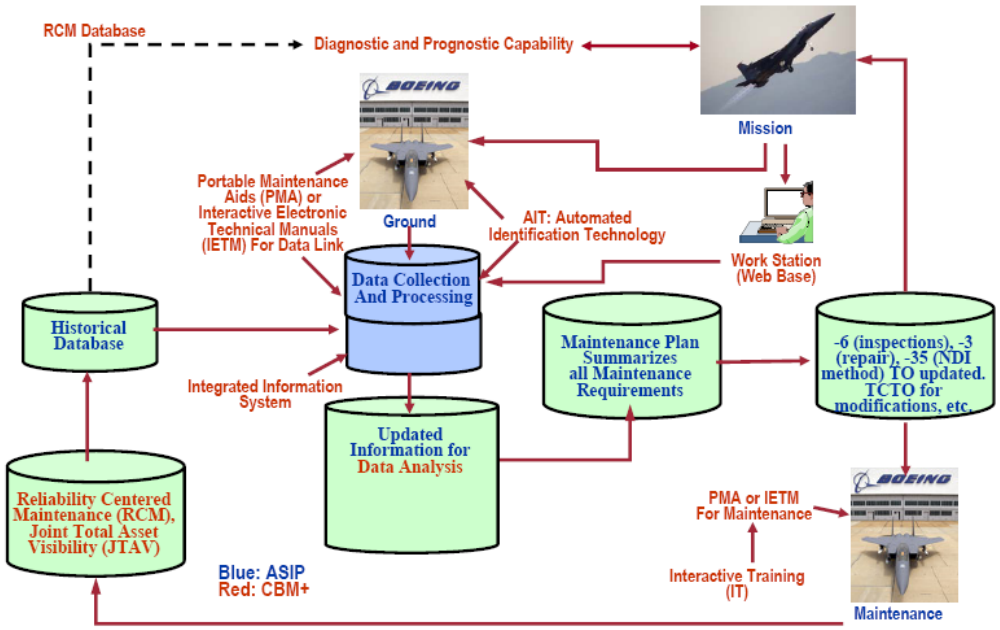


Figure I-2. CBM+ Architecture for the Demonstration Example

As shown in Figure I-2, all 10 CBM+ technologies and concepts are included:

Technologies
- Prognostics
- Diagnostics
- Portable Maintenance Aids
- Interactive Electronic Technical Manuals (IETMs)
- Interactive Training
- Data Analysis
- Integrated Information Systems
- Automatic Identification Technology

Concepts
- Reliability Centered Maintenance (RCM)
- Joint Total Asset Visibility

To incorporate all the above technologies into the CBM+SI architecture, both ASIP and CBM+ engineering analysis process as discussed in Steps 1 and 2 must be applied. The proposed CBM+SI architecture is shown in Figure I-3.

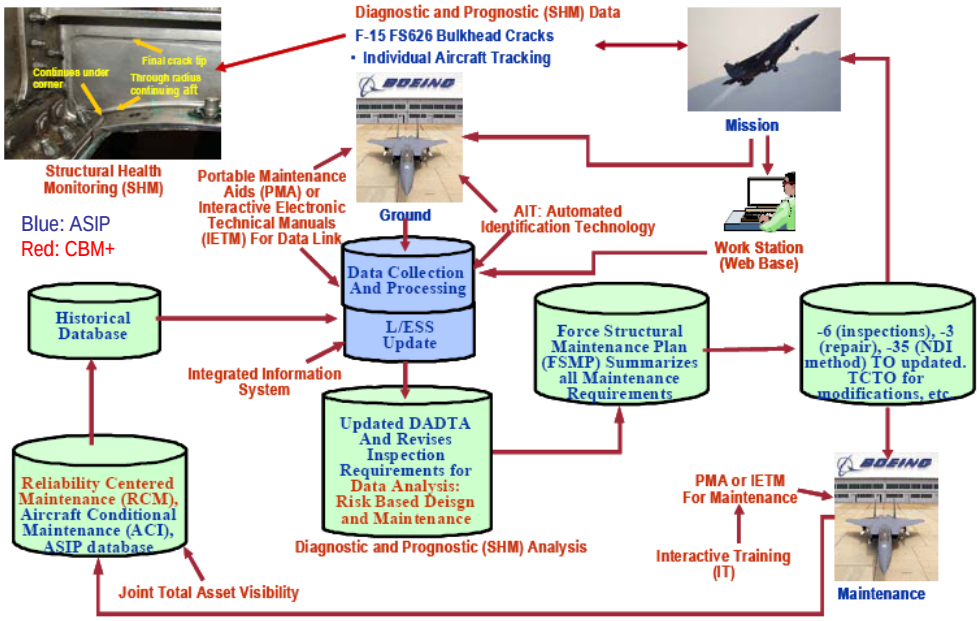


Figure I-3. CBM+SI Architecture

As discussed in the sub-section 1.1.1.1 Requirements, not all CBM+ technologies and concepts have been developed and can be applied for the demonstration example. Given limited budget and time, only the following key technologies from either ASIP or CBM+ are identified and required for the demonstration example:

1. ASIP risk assessment capability
2. Prognostic: Structural Health Monitoring (SHm)
3. Diagnostic capability from ASIP side: Individual Aircraft Tracking, Loads/Environment Spectra Survey, Forced Structural Maintenance Plan.
4. Information tool – Portable Maintenance Aid, Interactive Electronic Technical Manuals.
5. Advanced NDI
6. Reliability Center Maintenance
7. Joint Total Asset Visibility: Technical Performance Measurement (TPM) will be used to measure the benefits.

With the above needed technologies (with No. from 1 to 7) for the proposed demonstration example, an updated architecture is shown in Figure I-4. To implement these technologies, work remains to be completed are items 1, 2 and 7. Additional work for these items have been planned and will be implemented during the sub-section 1.1.2 “Demonstration”. Other CBM+ technologies or concepts that were not shown in Figure I-4 will be considered as technology gaps or to be implemented when there is a need in the future. In fact, the decision to add new or needed CBM+ technologies to the proposed CBM+SI architecture, the proposed CBM+SI continuous improvement process (as discussed in Appendix F) should be applied to make the right decision.

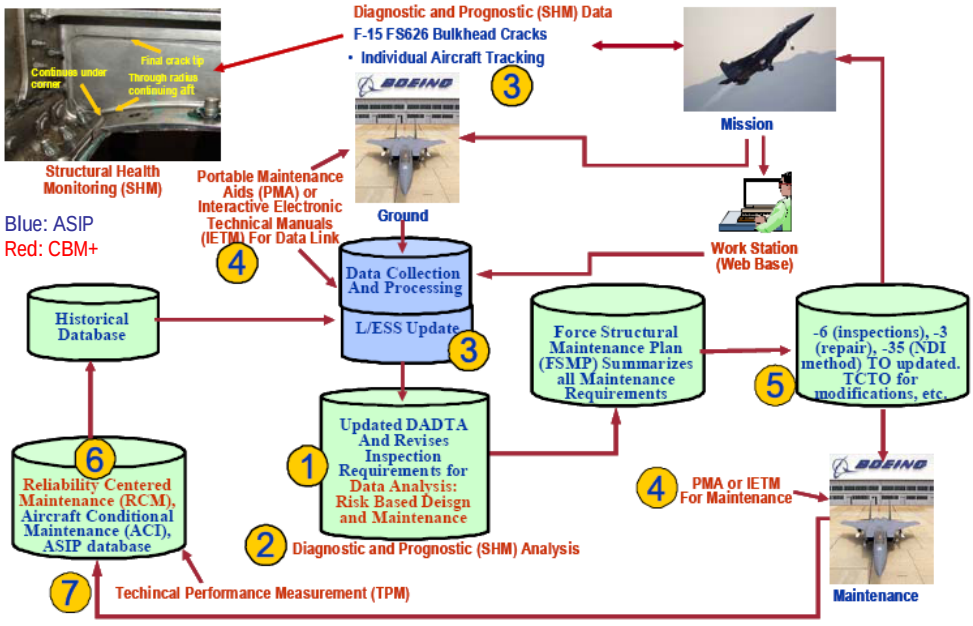


Figure I-4. CBM+SI Architecture for the Demonstration Example

With the proposed CBM+SI architecture for the demonstration example (Figure I-4), it is important to check if it will meet all key CBM+SI objectives:

- Developing integrated, predictive maintenance approaches, which minimize unscheduled repairs, eliminate unnecessary maintenance, and employ the most cost-effective maintenance health management approaches.
    - Advanced risk assessment strategy with consideration of the most cost-effective Structural Health Monitoring (SHm) capability will be developed to predict the optimal maintenance schedule.
- Determining an optimum mix of maintenance technologies.
    - With the advanced risk assessment strategy, the maintenance strategy includes traditional Non-Destructive Evaluation (NDE) or SHM can be considered and optimized given the cost constraint.
- Identifying the optimum opportunity to perform required maintenance.
    - As discussed, the proposed advanced risk assessment strategy will be able to predict the risk and these risk data should be applied by FSMP to identify the optimal opportunity to perform required maintenance.
- Providing real-time maintenance information and accurate technical data to technicians and logisticians.
    - With consideration of SHm, real-time maintenance information can be obtained and incorporated with traditional NDE inspection (preventive or corrective) data for risk assessment analysis process to predict the most optimal maintenance schedule for technicians and logisticians.

The other important question to ask is if the proposed architecture can be easily expanded to cover multiple control points, airframe, vehicle or aircraft, and fleet. The answer is yes because the proposed risk assessment strategy is flexible enough to predict the probability of failure for

the other types of failure modes. These data will be used by RCM and JTAV to track all the failure modes and develop the most cost-effective optimal maintenance plan.

In addition to the CBM+SI architecture, the "data flow" of the proposed architecture's key elements (1 through 7) will be discussed in the next subtask 1.1.1.3 "Data Flow" step 2. Note that the "requirements" of these key elements have been discussed in the subtask 1.1.1.1 "Requirement" step 3.

I.2 Step 4 Develop a Compliance Matrix for the Proposed CBM+SI Architecture and finalize CBM+SI Architecture Prototype

With the developed CBM+SI Architecture Prototype from Step 3(or section I.1), developed a compliance matrix to check if all the key CBM+SI elements have been considered and included:

1. Integrated individual tracking data with IVHM/SHM data,
2. Diagnostic and prognostic capabilities,
3. Enhanced maintenance quality,
4. Information tools, and
5. Total Life Cycle Systems Management (TLCSM).

Table I-1shows the comparison between the current ASIP and the proposed CBM+SI architecture for the demonstration example.

In addition to the above comparison, the developed CBM+SI architecture must be able to achieve the level 4 of the CBM+ pyramid as shown in Figure I-5. It is important to recognize the requirement in order to identify required CBM+SI technologies to demonstrate this level of benefit on the selected structural component.

Based on the compliance matrix, the proposed CBM+SI architecture will have the capability to perform predictive prognostics analysis, i.e., the level 4 of the CBM+SI pyramid. In other words, it will be able to estimate the expected Remaining Useful Life (RUL) for an individual asset (X within one standard deviation), based on past and future usages for the individual asset.

To predict the RUL and/or the optimal maintenance schedule, the proposed CBM+SI will apply an advanced risk assessment strategy coupled with the data provided from using the Structural Health Monitoring capability. The input data requirements for the risk assessment will include the OEM's lifing algorithms (i.e., crack growth curve and geometry curve), material properties/Red Book curves (i.e., fracture toughness), usage data (i.e., IATP data and L/ESS data - load exceedance curve), equivalent initial flaw size distribution, Non-Destructive Evaluation's Probability of Detection (POD), and many more input data.

Table I-1. Compliance Matrix for the Proposed CBM+SI Architecture

Five Major Technology Areas	ASIP (or SI) alone	CBM+SI for selected demonstration example
Integrated Individual tracking data with IVHM/SHM data	none	Yes, SHM (task 1.1.2.2) will be applied.
Diagnostic and prognostic capabilities	Diagnostic only (IATP, L/ESS)	Yes, both diagnostic and prognostic (task 1.1.2.3), Advanced risk assessment strategy will be developed to predict the risks for ranking and sensitivity analysis.
Enhanced maintenance quality	Yes, advanced NDI and repair technology.	Yes, advanced NDI and repair technology.
Information tools	Yes, PMA, IETM will be applied.	Yes, PMA, IETM will be applied.
Total Life Cycle Systems Management (TLCSM)	none	Yes, TLCSM will be measured via TPM (task 1.1.2.5)

Based on the above observations, it demonstrates that the proposed CBM+SI architecture will be able to achieve the "predictive prognostic" level 4's capability.

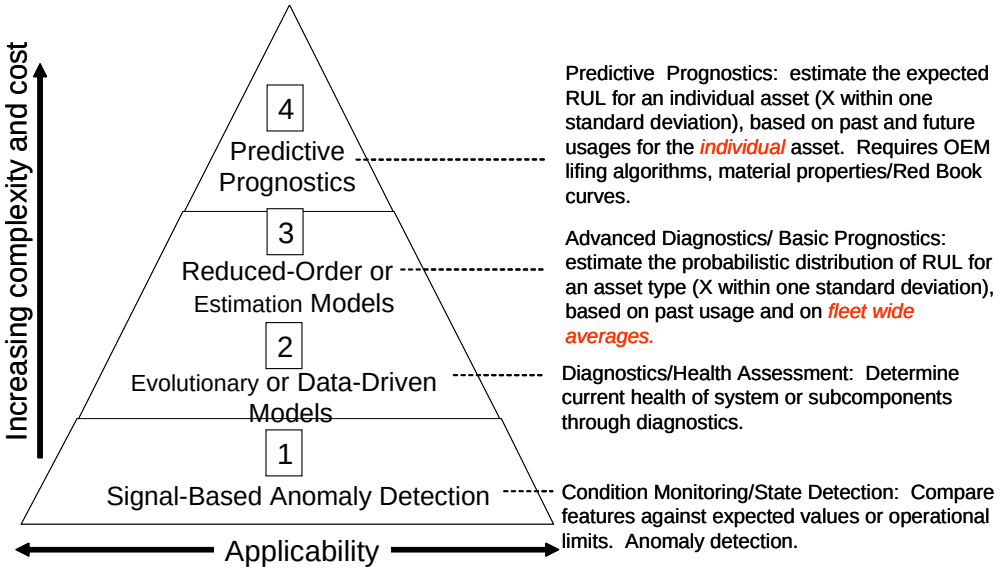


Figure I-5. CBM+SI Pyramid chart

Appendix J. Data Flow

The main objective of this task is to define the data flow of the developed architecture prototype. All the data shall be collected and stored within the historical database for further decision making cycles and future designs. To implement the task, ASIP reliability and risk assessment data flow and data requirement will be studied first and used as a reference for CBM+SI reliability and risk assessment data flow.

J.1 Study Current ASIP Reliability And Risk Assessment Data Flow And Its Data Requirements

The current ASIP reliability and risk assessment data flow used to determine the maintenance schedule based on the MIL-STD-1530C will also play a major role for CBM+SI. Therefore, it is necessary to study and define the data flow for the risk computational strategy based on crack growth curve, geometry curve, IAT's Load Spectrum data, material data, NDE POD, EIFS, etc.

As shown in Figure J-1, it shows the essence of damage tolerance design approach applied to protect safety at each fatigue control point. This Figure first shows how the Program identified the control points, updated the stress spectra, and created the EIFS. Based on these data and the proposed fatigue crack growth life prediction (damage tolerance) models, the safety limits (based on deterministic safety factor approach), inspection requirements, onset of Widespread Fatigue Damage (WFD) and modification/replacement requirements were identified. Then, these data will be used to modify options and aircraft assessment strategy by updating the FSMP plan and IATP plan.

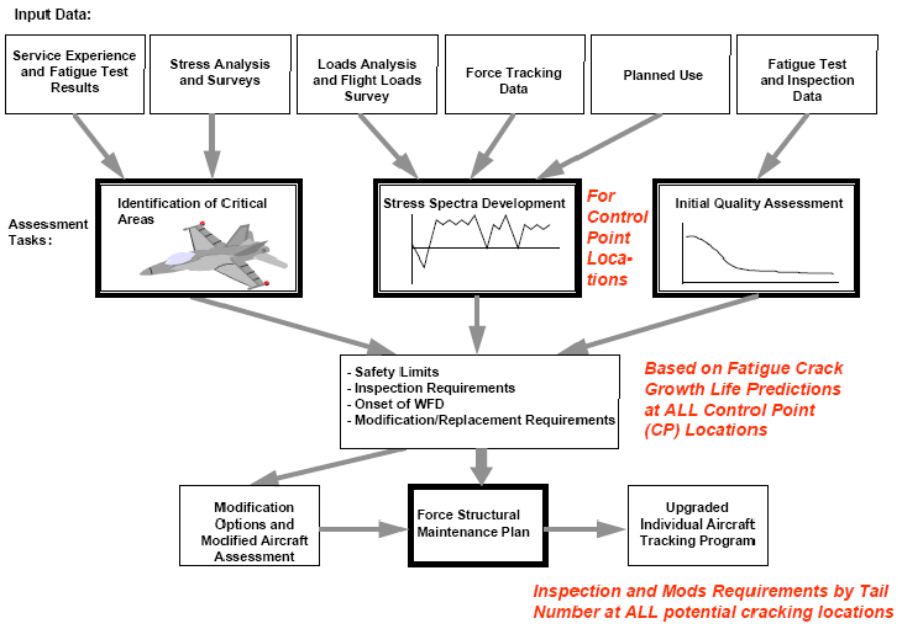


Figure J-1. The Essence of the Damage Tolerance Design Approach Applied to Protect Safety At Each Fatigue Control Point

From the proposed damage tolerance design approach, the risk assessment plays an important role in replacing the traditional deterministic safety factor approach to assess the optimal maintenance schedule. The input parameters for the risk assessment are actually the same input data used by the traditional deterministic safety factor approach but risk assessment approach

calculates the single flight probability of failure (SFPoF) to compare with the requirements stated in MIL-STD-1530C. As illustrated in Figure J-2, the risk assessment input parameters are illustrated and these data can be broken into three major parts:

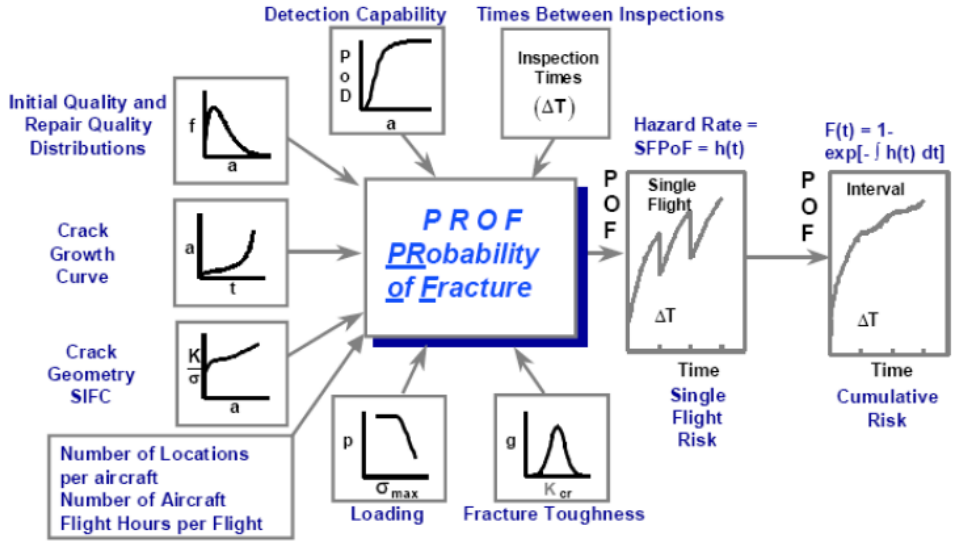


Figure J-2. Risk Assessment Input Parameters

1. Material/Geometry
   a. K/sigma vs. a - a data file
   b. Kc - a Normal distribution with mean and standard deviation
2. Aircraft/Usage
   a. Locations in an aircraft
   b. Total number of aircraft
   c. Average flight length.
   d. Initial crack size - a single distribution (lognormal with mean and standard deviation) or a mixed distribution (with distributions, distribution parameters, and percentage of each distribution)
   e. Critical crack size - must be identified
   f. Crack size vs. Time file - a data file
   g. Stress - a Gumbel distribution
3. Inspection/Repair
   a. Time to inspection, total number of inspections, time1, time2, etc.
   b. POD - parameter values - a cumulative lognormal POD function will ask for median detectability, steepness, and smallest detectable crack.
   c. Repair crack size - a distribution or mixed distributions with percentage of distribution defined

At the center block, it shows a computation tool named “Probability of Fracture (PROF)” code, which was developed by the University of Dayton Research Institute and sponsored by the Air Force. At The Boeing Company, a Reliability-Based Design and Maintenance System (RBDMS) code was developed to perform the same computational efforts but using different computation engine. The PROF/RBDMS code will apply all the input data and calculate the SFPoF and compare with the 1.E-7 requirement and determine the inspection schedule. At the time of inspection, the percentage of crack found will be calculated based on the inputted NDE

POD parameters and then the crack size distribution will be updated. With the updated crack size distribution, the analysis process will repeat itself by calculating the next SFPoF and percentage of crack found.

The above process did not show clearly in Figure J-2 but is shown in Figure J-3. As shown in Figure J-3, the left side block contains all the needed input parameters which are the same as shown in Figure J-2. Then, based on all input parameters, the program first performs its crack growth analysis to the first selected time interval. The crack size distribution will start from the EIFS input and grows to an updated crack size distribution. This crack size distribution will then be used in calculating the SFPoF value. If the calculated SFPoF value is less than the required 1.E-7, the crack should continue to grow until it reaches the limit. The process will continue until the crack grows to a size where its SFPoF is very close to the required 1.E-7 value (preferred it is smaller than the 1.E-7 limit). The time it reaches the limit will be selected as the first inspection interval.

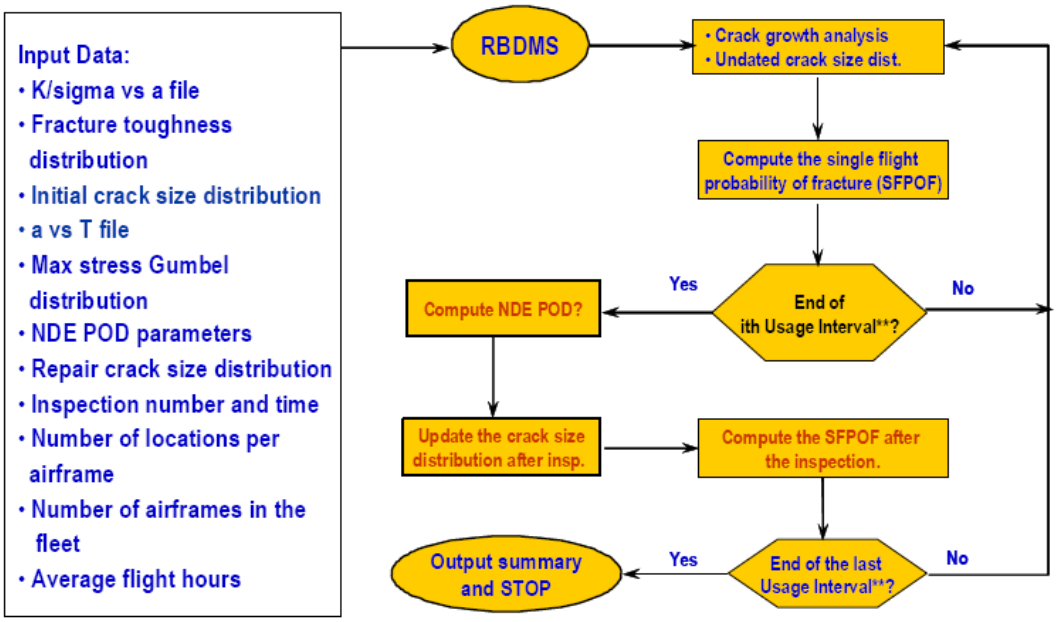


Figure J-3. Risk Assessment Analysis Process

After the first inspection interval was selected, the crack size distribution will be used to compute the percentage of crack found based on the selected NDI POD parameters. The crack size distribution will then be updated based on the percentage of cracks have been found and repaired and those have not been found.

After the inspection step, the updated crack size distribution will be used to compute the SFPoF and compare with SFPoF before the inspection. The purpose of this step is to justify the impact of NDI inspection. After this SFPoF calculation step, the updated crack size distribution will be used to perform the crack growth analysis by running the above process until the selected total no. of inspections has been reached.

Appendix K. Beta Testing

The objective of this task is to develop a beta testing plan based on the proposed CBM+SI architecture prototype (sub-section 1.1.1.2) to demonstrate CBM+SI benefits on the selected structural component using the proposed TPM analysis. In addition, the technology shortcomings and gaps needed for a successful demonstration will also be identified and summarized.

K.1 Beta Testing Plan

The selected testing cases within the beta testing plan will be executed during the demonstration phase. For comparison purpose, the baseline case must be defined first and the original ASIP FSMP process by using a deterministic safety factor approach will be considered. The other testing cases must be able to: develop an optimum predictive maintenance approach through the integration of data; apply advanced risk based methods and cost benefits modeling to eliminate unnecessary maintenance and minimize unscheduled repairs; and establish a cost-effective health management approach for inspections and logistics needs.

To achieve the above benefits, the proposed CBM+SI strategies must consider the following five key elements as discussed in the proposed CBM+SI architecture prototype:

1. Integrated individual tracking data with IVHM/SHM data,
2. Diagnostic and prognostic capabilities,
3. Enhanced maintenance quality,
4. Information tools, and
5. Total Life Cycle Systems Management (TLCSM).

With these key elements, as shown in Table I-1, a compliance matrix between ASIP and CBM+SI architecture was developed and compared. For the beta testing cases, the same figure will be developed to compare the technologies used in each beta testing case and shown in Table K-1. These beta testing cases are also summarized in the following:

1. Baseline case: This case is based on the traditional ASIP analysis process by using a deterministic safety factor approach to determine the maintenance schedule
2. Test case 1: Baseline + risk based approach. This option only replaced the traditional deterministic safety factor approach with a new risk-based approach.
3. Test case 2: SHM Boolean – single zone + risk-based approach + other CBM+ capabilities. This option considers implementing a SHM Boolean - single zone capability. The risk-based approach will be updated to reflect the SHM data input.
4. Test case 3: SHM Boolean – multiple zones + risk-based approach + other CBM+ capabilities. This option considers implementing a SHM Boolean - multiple zone capability and its data will be integrated and used by risk-based approach.

Note that for test cases 2 and 3, because this is a retro-fit application, all data acquisition hardware and software will be off-board so as not to incur any weight or system penalties. As shown in the Table K-1, there are other key elements within CBM+SI will be considered. However, those factors will have minor or no impact to the maintenance schedule except that Advanced NDI capability may be applied when SHM capability does not have high fidelity readings. These options may be discussed later when these beta testing cases are solved during the demonstration phase.

Table K-1. Beta Testing Cases

Five Major Technology Areas	Baseline ASIP	Test Case 1.	Test Case 2.	Test Case 3.
Integrated Individual tracking data with IVHM/SHM data	none	none	Yes, SHM with Boolean – single zone capability	Yes, SHM with Boolean – multiple zone capability
Diagnostic and prognostic capabilities	Diagnostic only (IATP, L/ESS)	Diagnostic (Advanced risk assessment strategy will be developed to predict the risks for ranking and sensitivity analysis)	Diagnostic and Prognostic (SHM and Advanced risk assessment strategy will be developed to predict the risks for ranking and sensitivity analysis)	Diagnostic and Prognostic (SHM and Advanced risk assessment strategy will be developed to predict the risks for ranking and sensitivity analysis)
Enhanced maintenance quality	Yes, advanced NDI and repair technology.	Yes, advanced NDI and repair technology.	Yes, advanced NDI and repair technology.	Yes, advanced NDI and repair technology.
Information tools	Yes, PMA, IETM will be applied.	Yes, PMA, IETM will be applied.	Yes, PMA, IETM will be applied.	Yes, PMA, IETM will be applied.
Total Life Cycle Systems Management (TLCSM)	none	Yes, TLCSM will be measured via TPM (task 1.1.2.5)	Yes, TLCSM will be measured via TPM (task 1.1.2.5)	Yes, TLCSM will be measured via TPM (task 1.1.2.5)