SAFE AND ECONOMIC MANAGEMENT OF WIDESPREAD FATIGUE DAMAGE (WFD) USING PROGNOSTIC/DIAGNOSTIC HEALTH AND USAGE MONITORING

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ABSTRACT:

As the world aircraft fleet ages, there is increasing concern about the development of Widespread Fatigue Damage (WFD). This has resulted in regulatory agencies and Original Equipment Manufacturers (OEM) proposing and/or developing regulations and service bulletins to address WFD that from an inspection/maintenance perspective are onerous to apply, costly to implement and in some instances of questionable reliability.

The main approach to dealing with WFD is to establish a design service goal, together with a limit of maintenance validity during which it is anticipated that WFD will not occur. The Design Service Goal that is chosen is primarily to be substantiated by full-scale fatigue test data which has been obtained from a test using a spectrum which is considered representative of anticipated aircraft usage.

Given the operational life-span of many aircraft it is debatable as to how representative the spectrum used in an original fatigue test will remain of actual usage experienced by aircraft nominally remaining in their design role. This problem is further exacerbated when aircraft are converted for use in special mission roles such as aerial firefighting, geophysical survey or special mission operations for which they were not originally designed. Consequently, the question arises can a safe and economic method of addressing WFD concerns be developed for aircraft at a stage in their life cycle where they are economically viable to operate but uneconomically viable to substantiate with an additional full-scale fatigue test, truly representative of their actual operational usage?

This paper proposes a prognostic/diagnostic approach to Health and Usage Monitoring that may provide at least an Equivalent Level of Safety to that intended by current WFD guidelines being proposed by regulatory agencies. As such, it would provide an Alternate Means of Compliance (AMOC) to pending regulatory and service bulletin approaches. The method is based on combining a cost-effective Health and Usage Monitoring System with Comparative Vacuum Monitoring (CVM) technology to ascertain the actual loads to which an aircraft is being subjected while at the same time providing an early indication of the development of any WFD in critical areas. The data that is obtained is subject to ongoing analytical/experimental evaluation, such that the prognostic capabilities of the health and usage monitoring data combined with the diagnostic crack-detection capabilities of the CVM technology provide a viable, safe and economic approach to addressing WFD concerns.
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<tr>
<td>AASFR</td>
<td>Aging Airplane Safety Final Rule</td>
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<td>AATF</td>
<td>Airworthiness Assurance Task Force</td>
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<td>AAWG</td>
<td>Airworthiness Assurance Working Group</td>
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<td>AC</td>
<td>Advisory Circular (FAA)</td>
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<td>AD</td>
<td>Airworthiness Directives (FAA)</td>
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<td>ALS</td>
<td>Airworthiness Limitations Section</td>
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<td>AMOC</td>
<td>Alternate Means of Compliance</td>
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<td>ARAC</td>
<td>Aviation Rulemaking Advisory Committee</td>
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<td>ASIP</td>
<td>Aircraft Structural Integrity Program</td>
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<td>CPCP</td>
<td>Corrosion Prevention and Control Program (AAWG)</td>
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<td>CVM</td>
<td>Comparative Vacuum Monitoring</td>
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<td>DAH</td>
<td>Design Approval Holder</td>
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<td>DSG</td>
<td>Design Service Goal</td>
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<td>ELOS</td>
<td>Equivalent Level of Safety</td>
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<td>EOL</td>
<td>Extended Operational Limit</td>
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<td>ESG</td>
<td>Extended Service Goal</td>
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<td>FAA</td>
<td>Federal Aviation Administration (FAA)</td>
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<td>FSFT</td>
<td>Full-Scale Fatigue Test</td>
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<td>ICA</td>
<td>Instructions for Continuing Airworthiness</td>
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<tr>
<td>IOL</td>
<td>Initial Operating Limit</td>
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<tr>
<td>ISP</td>
<td>Inspection Start Point</td>
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<td>LOV</td>
<td>Limit of (Maintenance) Validity</td>
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<td>MED</td>
<td>Multi-Element Damage</td>
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<tr>
<td>MGTW</td>
<td>Maximum Gross Take-off Weight</td>
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<td>MMP</td>
<td>Mandatory Modification Program (AAWG)</td>
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<td>MSD</td>
<td>Multi-Site Damage</td>
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<td>NDI</td>
<td>Non-Destructive Inspection</td>
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<td>NPRM</td>
<td>Notice of Proposed Rule Making (FAA)</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>NTSB</td>
<td>National Transportation Safety Board (U.S.)</td>
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<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>PSE</td>
<td>Principal Structural Element</td>
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<td>RAP</td>
<td>Repair Assessment Programs (AAWG)</td>
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<td>SHM</td>
<td>Structural Health Monitoring</td>
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<td>SMP</td>
<td>Structural Modification Point</td>
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<td>SSHMP</td>
<td>Strategic Structural Health Management Plan</td>
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<td>SSID</td>
<td>Supplemental Structural Inspection Document (AAWG)</td>
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<td>STG</td>
<td>Structures Task Group (AAWG)</td>
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<tr>
<td>TC</td>
<td>Type Certificate</td>
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<tr>
<td>WFD</td>
<td>Widespread Fatigue Damage</td>
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<td>$WFD_{\text{average}}$</td>
<td>The time at which WFD will be present in 50% of an aircraft fleet</td>
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1 INTRODUCTION

Recently the Federal Aviation Administration (FAA) issued some Notices of Proposed Rule Making (NPRM) aimed at addressing Widespread Fatigue Damage within the large transport category aircraft fleet\(^1\)[2]. Within the context of the proposed NPRMs, large transport aircraft are considered to be aircraft with a Maximum Gross Take-off Weight (MGTW) greater than 75,000 lbs. To support the proposed NPRMs the FAA are proposing to issue and/or re-issue a number of Advisory Circulars (AC). These include, but are not limited to References [3], [4], [5] and [6].

The proposed FAA recommendations will have severe operational and financial implications, particularly with regard to the:

- conversion of aircraft from the commercial fleet for cargo applications\(^7\);
- conversion of aircraft for use in special mission roles such as aerial firefighting or other related low-level roles\(^8\); and
- aviation infrastructure, commerce and relief activities in remoter parts of the continental USA and developing countries.

If the proposed regulations were implemented in their entirety, it would no longer be commercially viable to operate many existing aircraft operating nor to convert future aircraft to operate in these roles \(^8\)[9][10][11][12]. A number of existing fleets would have to cease operations immediately and consequently the associated asset value of the aircraft would become negligible overnight.

The devastating impact that the proposed regulations could have on current and future aircraft fleets can primarily be attributed to:

- The assertion that the Design Approval Holder (DAH) is the only organization capable of generating the Initial Operational Limit (IOL) required for the continued operation of many of the aircraft\(^1\);
- The implication that only a Full-Scale Fatigue Test (FSFT) can generate the required WFD data for these aircraft\(^3\), even though other documentation indicates that the FSFT is only one possible source of “fatigue evidence”. Furthermore, given the stage in their life cycle, it would no longer be economically viable to conduct an FSFT for many existing operational aircraft;
- The assumption that there is currently no effective way of detecting WFD\(^7\);
- The contradiction associated with the need to implement the proposed WFD regulations for large transport category aircraft immediately, versus the rationalization for exempting regional jets in violation of the FAA's own “One-Level of Safety Policy”\(^1\)[13]; and
- The validity of the rationale supporting the initial specification of Design/Extended Service Goals\(^9\)[10][11] not being supported by actual operational experience.
While WFD is a real problem with significant safety implications, it is worthwhile noting that to date there has not yet been a catastrophic accident that has been solely attributed to WFD. In part, this is a testimony to the effectiveness of a number of programs that have been implemented to address aging aircraft structural issues since the infamous Aloha Airlines Boeing 737 incident in 1988. Therefore, while it is appreciated that in defining regulations safety is of paramount importance, the question arises as to whether there are Alternate Means of Compliance (AMOC) that would provide an Equivalent Level of Safety (ELOS) to that afforded by the proposed regulations, without such devastating commercial consequences?

This paper proposes a possible Alternate Means of Compliance that particularly for older aircraft, would provide an economically viable method of addressing WFD concerns while still maintaining what appears to be the intent of the regulations proposed by the FAA in their recent NPRM.

2 PROPOSED APPROACHES FOR MANAGING WFD

To provide a context against which the merits of the alternate approach can be assessed, it is first necessary to consider:

- Why WFD became an issue?
- How has WFD been addressed in the past?
- How is FAA proposing to Address WFD in the Future? and
- The Commercial Implications of the Proposed Approach.

These issues are discussed in more detail in Sections 2.1 to 2.4.

2.1 Why did WFD Become an Issue?

The problem of fatigue in aircraft structures first gained prominence with the introduction of the commercial jet age in the early 1950’s. The failure of two de Havilland Comet aircraft within a few months and the subsequent investigation demonstrated that aircraft designers must account for and design to prevent metal fatigue. Initially, the main area of concern was that of manufacturing and/or design flaws. These caused localized cracking in critical structure which subsequently propagated to the point where the remaining (residual) strength of the structure could no longer sustain normal flight loads. Following the failure of the Comet, a number of regulatory agencies introduced airworthiness requirements aimed at ensuring that metal fatigue was properly addressed and managed. As the science (or more accurately the art) of fatigue detection and management developed, different management approaches were progressively refined in response to different operational incidents. Between the mid 1950s and the mid 1970s the aerospace industry progressed from the Safe Life approach (replace a component before any likelihood of failure), through the Fail-Safe approach (use
redundant structure so that if failure occurs there is a back-up plan) to the Damage Tolerance approach. Damage Tolerance was in many ways considered to be the culmination of the aerospace industry’s “battle with fatigue”. Its strength lay in the marrying of analytical prediction with inspection and maintenance techniques to ensure that should a crack develop in a critical structural location, the probability of it propagating to the point of failure without first being detected and addressed was acceptably small.

Although the Damage Tolerance approach provided a more robust and arguably more realistic approach to managing fatigue than did the original Safe Life approach, the underlying principle for both approaches remained the same: i.e.: the “enemy” was a localized crack emanating from a manufacturing or design flaw. However, the adequacy of this basic tenet was called into question following the in-flight structural failure of the fuselage of an Aloha Airlines Boeing 737 in April 1988[15]. During the flight a lap joint that had developed multiple small cracks, which in and of themselves had not attained a critical size and were indeed barely detectable, unzipped and peeled back a large section of the upper fuselage. While the failure itself was serious, what was even more alarming was that in the ensuing investigation it was discovered that the cracks developed primarily as a result of the fatiguing, or a wearing-out, of the structure. Aloha Airlines were using their Boeing 737s for many short-haul flights between the Hawaiian Islands; consequently, they had been subjected to a very high number of pressurization cycles.

The Aloha Airlines failure identified the need to address what was subsequently termed Multi-Site Damage (MSD). MSD can precipitate catastrophic structural failure as a result of the development and linking-up of barely detectable multiple cracks, in an area in which the stress level is sensibly similar, prior to their detection. The Aloha Airlines failure identified a need to pay particular attention to aircraft which had accumulated a high number of flight cycles. As invariably a high number of flight cycles were associated with older aircraft, the aftermath of the Aloha incident gave rise to the so-called Aging Aircraft Program which was launched in the early 1980s[14].

2.2 How has WFD Been Addressed in the Past?

To assist their deliberations on how best to address the aging aircraft problem, the FAA recruited the help of a number of industry experts and formed the Airworthiness Assurance Task Force (AATF) in 1988. This group was subsequently renamed the Airworthiness Assurance Working Group (AAWG) of the Aviation Rulemaking Advisory Committee (ARAC) which was formed by in 1991.

Many of the aging aircraft in existence at the time the AAWG was formed had not been designed on a damage tolerant basis as this had not been made a regulatory requirement until the introduction of FAR 25.571 Amendment 45 in December 1978. Consequently, the AAWG decided that their first priority was to implement programs for non-damage tolerant certified aircraft that would subject them to an equivalent level of inspection and maintenance scrutiny as that to which damage tolerance certified aircraft were subjected. The AAWG defined a number of programs, some of which have been subsequently implemented on the different aging aircraft fleets by aircraft specific Structures Task Groups (STGs). These programs were the[14]:

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_Celeris Aerospace Canada Inc / Structural Monitoring Systems_
1. **Mandatory Modification Program (MMP).** The identification of structurally significant service bulletins and recommended mandatory incorporation of modifications;

2. **Corrosion Prevention and Control Program (CPCP);**

3. **Generic Structural Maintenance Program guidelines for aging aircraft;**

4. **Supplemental Structural Inspection Documents (SSID);** and

5. **Repair Assessment Programs (RAP).**

At the same time as the AAWG was developing these programs, a considerable amount of research and development was undertaken to understand the cause of the Multi-Site Damage phenomena that had been cited as a contributory factor in the Aloha incident (other factors being poor inspection and maintenance practices). As a consequence of this work, it was realized that Multi-Site Damage was one part of a broader problem termed Widespread Fatigue Damage (WFD). The other part of WFD was subsequently termed Multi-Element Damage (MED). Whereas Multi-Site Damage refers to multiple damage propagation (cracks) in a single structural element, Multi-Element Damage refers to multiple damage propagation in adjacent structural elements.

Even though there has yet to be an accident that can be directly attributed to WFD, it was recognized that given the increasing average age of the commercial fleet, WFD needed to be addressed. Consequently the AAWG was assigned a sixth task by the FAA, namely:

6. **Recommend procedures to preclude the occurrence of widespread fatigue damage within the transport airplane fleet**[^14].

Although WFD appears to be a specific instance of damage involving small cracks, detecting it proved to be quite challenging. The size of the cracks that can rapidly link-up and causes failure are often at or below the threshold of detection of many commonly used NDI techniques. Therefore, as there is a very small detection window the risk that WFD might not be detected prior to it reaching a critical state is high. Consequently, the principle that was been adopted with regard to dealing with WFD was one of “avoidance”.

Using a number of different analytical and experimental techniques, attempts have been made to establish a goal or a limit that would sensibly ensure that WFD would not occur during the operational lifetime of an aircraft. Until this limit or goal is reached, the basis of an aircraft’s inspection and maintenance program is the application of damage tolerance principles, i.e. dealing with localized cracking as a result of a manufacturing or design flaw. Once the goal or limit is reached, an aircraft needs to be revaluated. If no evidence of WFD is found then there is the possibility of extending the goal or limit. If evidence of WFD is found, then without structural modification/replacement of the affected structure, life extension cannot be contemplated.
2.3 How Is the FAA Proposing To Address WFD In The Future?

In their latest NPRM[1] and one of its associated Advisory Circulars[5], the FAA describes its future approach to managing WFD. An Initial Operating Limit (IOL) will have to be established for all future transport category aircraft applying for a Type Certificate and all current transport category aircraft with a Maximum Gross Take-off Weight (MGTW) in excess of 75,000 lbs. Furthermore, it is considered that the only organization that is capable of establishing an IOL acceptable to the FAA is the Design Approval Holder (DAH) who has access to all the engineering data (In practice the Original Equipment Manufacturer (OEM) or the current holder of the Type Certificate (TC)). For reasons that will be presented in Section 2.4.1, such an assertion has implications which will effectively ground many viable aircraft.

The IOL is defined as a limit, established by a fatigue evaluation of an aircraft beyond which WFD might occur[8][14]. This limit is to be incorporated into the Airworthiness Limitations Section (ALS) of the Instructions for Continuing Airworthiness (ICA) for the aircraft. As such it constitutes a limit on aircraft usage that cannot be exceeded unless a prior Extended Operational Limit (EOL) has been negotiated with the FAA. The proposed application of the IOL is illustrated schematically in Figure 1.

As illustrated in Figure 1(a), the first step in establishing an IOL is to develop an estimate of the number of cycles at which it is anticipated that 50% of an aircraft fleet will have developed WFD. This estimate is termed WFD_{average}. Based on the value of WFD_{average}, a Structural Modification Point (SMP) can then be established.

An SMP is the point at which an operator is required to implement structural modification/replacement to avoid the occurrence of WFD. The SMP can be defined in one of two ways. If it can be demonstrated that there is an effective method of inspection that can reliably detect the occurrence of WFD prior to it becoming critical (i.e. the residual strength of the affected structure can still sustain limit flight loads) the SMP can be set to the number of flight hours/cycles that corresponds to half the value of WFD_{average}. Conversely, if it cannot be demonstrated there is an effective method of inspection that is capable of detecting WFD prior to it becoming critical then the SMP can be set to the number of flight hours/cycles that corresponds to a third of the value of WFD_{average}.

In those instances where an effective inspection method for detecting WFD can be demonstrated, an inspection program has to be implemented with a view to detecting and addressing WFD prior to the SMP being attained. The times at which the WFD inspections have to commence, termed the Inspection Start Point (ISP), depend on the data that is available with regard to the degree of effectiveness of the inspection itself. If a statistically valid distribution related to the ability of the inspection method to detect cracks is not available, then the ISP has to be established at WFD_{average}/3. Conversely, if a statistically valid distribution related to the ability of the inspection method to detect cracks is available then the ISP can be set at an acceptable lower bound of the distribution. This lower bound will fall somewhere between WFD_{average}/3 and WFD_{average}/2.
Figure 1: Schematic Illustration of Proposed FAA IOL Implementation
The application of a WFD inspection program is very similar to that incorporated in the damage tolerance approach as illustrated in Figure 1(b). The interval between the ISP and the SMP is divided into a number of intervals based on the method of inspection used and its associated reliability. This provides multiple opportunities to detect and address WFD prior to it becoming critical.

There is one inference in the proposed FAA documentation that is puzzling. As illustrated in Figure 1(b), it is implied that inspections should commence prior to the MSD/MED being detectable. From a practical perspective, the rationale for inspecting for damage before it is detectable using the prescribed inspection technique is difficult to comprehend. It suggests that the effectiveness of the inspection is questionable and therefore based on the proposed regulations the SMP should be set at $WFD_{average}/3$ as opposed to $WFD_{average}/2$.

Having established how an IOL is defined, the FAA relates it back to how the aircraft was designed. FAR 25.571 Amendment 45 and beyond establishes the concept of a Design Service Goal (DSG) which is defined as:

\[ \text{"the period of time (in flight cycles/hours) established at design and/or certification during which the principal structure will be reasonably free from cracking"}^{[16]} \]

Included in the concept of the DSG is the possibility of an Extended Service Goal (ESG). This is an extension of the DSG which is based on additional fatigue evidence (e.g. additional fatigue testing and/or operational service experience) which indicates that the original DSG can be extended. Additional fatigue evidence can include lack of evidence of fatigue cracking and/or the implementation of structural modification(s). In fact, in the proposed NPRM the FAA suggests that a reasonable period for which an ESG should be demonstrated is 1.25 times the DSG. Consequently, for most practical applications, the IOL is going to equal the DSG/ESG. In turn, this value will also equal the ISP if it has been demonstrated that there is an effective method of identifying WFD prior to it becoming critical. If there is no effective inspective method (Figure 1(b)), then the IOL is set to the SMP. This raises the interesting possibility that if the DSG/ESG is set below the IOL and the aircraft is not used beyond its DSG/ESG, WFD will not become an issue that needs to be addressed during the operating life of the aircraft.

Also included in the latest NPRM is the concept of an Extended Operational Life (EOL) which can be granted if it can be demonstrated as a result of additional testing and/or the implementation of modifications that WFD will not occur in the airplane up to the proposed EOL.

## 2.4 The Commercial Implications of the Proposed Approach

As previously noted, if implemented in its present form the proposed NPRM would have a significant and detrimental impact on operators with older aircraft in general and operators of special mission aircraft (aircraft operating in roles which were not necessarily envisioned during their original design) in particular. The main reason for this is that there are still a significant number of aircraft in operation that were certified prior to the introduction of damage tolerance (FAR 25.571 Amendment 45). As such,
there was no regulatory requirement for a Full-Scale Fatigue Test (FSFT). At this stage in their life-cycle the economic viability of implementing a FSFT will be extremely questionable. Consequently, regardless of whether or not the aircraft are currently experiencing WFD, significant numbers of aircraft may well be grounded immediately. As noted or implied in References [8] through [12] and [17], in addition to the commercial costs associated with the grounding of these aircraft, there could also be a large socio-economic cost. Many of these aircraft provide vital infrastructure support to remote communities or communities in crisis. Even assuming the funding were available to obtain replacement aircraft, it is noted that in many circumstances there are no suitable replacement aircraft with equivalent capabilities that can sustain the harsh demands of the environment(s) in which these aircraft operate.

Many of the submissions made in response to the proposed NPRM (http://dms.dot.gov/search/document.cfm?documentid=404537&docketid=24281) comment that safety benefits that are obtained would be marginal at best; and certainly not commensurate with the cost. Some of the primary reasons for this response can probably be attributed to the issues that are outlined in Sections 2.4.1 to 2.4.5.

2.4.1 Limiting the Definition of an IOL to the DAH

Reference [1] states:

“We (the FAA) believe that the safety objectives contained in this proposal can only be reliably achieved and acceptable to the FAA if the DAHs provide operators with the initial operational limits required by the proposed operational rules for parts 121 and 129”

While such an approach may be viable for future type certifications, it can cause significant problems for the continued operation for existing aircraft that were certified prior to the introduction of damage tolerance requirements (i.e. under Car 4b or pre-FAR 25.571 Amendment 45). The question arises as to what happens if the DAH decides for non-safety reasons, e.g. insufficient economic benefit, adverse effects on sales of newer aircraft or unacceptable liability exposure, that they do not wish to pursue establishing an IOL or EOL for their aircraft?[8][18]. While the FAA acknowledges this could be an issue[1], their current proposal does not appear to adequately address the economic impact to an operator in this position who would have little to no choice but to ground their aircraft. Ironically, this is a position which the FAA categorically states in the following section of the NPRM they are anxious to avoid.

Although it is useful to have the collaboration of the DAH when developing an IOL for an existing aircraft, it is not essential. It is possible to reverse-engineer data for critical components. This approach has been used to apply for and/or obtain an Equivalent Level of Safety finding as an alternate method of compliance for aircraft operating in the aerial firefighting role[19][20].

Contrary to the generation of an IOL, it appears that the generation of an EOL does not lie solely within the purview of the DAH even though generating an EOL may, in some instances, require as much knowledge and experience as that required for the generation of the IOL. Therefore, for existing aircraft that were certified pre FAR 25.571 Amendment 45, if the FAA considers that organizations other than the DAH may be...
competent enough to generate an EOL, it is difficult to comprehend why such organizations would be precluded from substantiating an IOL.

2.4.2 Requirement for Full-Scale Fatigue Testing

In the WFD NPRM\(^1\) and some of the presentations made by those involved in the AAWG\(^{[21]}\) there is a suggestion that the long-term durability of an aircraft and its susceptibility to WFD can be based on fatigue test evidence other than that obtained from a full-scale fatigue test. Unfortunately, one of the accompanying Advisory Circulars suggests that the FAA is very much tied to substantiating the WFD capability of an aircraft that undergoes modification and/or change of mission with a Full-Scale Fatigue Test\(^3\) (See Appendix C of Reference [3]). In many instances, aircraft undergoing modification and/or a change of role tend to be older aircraft and as such the validation of their WFD by a full scale fatigue test might be impractical as:

1. If the aircraft was certified pre FAR 25.571 Amendment 45, there was no requirement for a Full-Scale Fatigue Test. Hence generating full-scale fatigue test data is not just an issue of resuming a previous test (assuming the design, jigs etc are still around), but rather a case of developing an FSFT from scratch. In many instances, this would not be economically viable;

2. If the aircraft was certified at FAR 25.571 Amendment 45 or beyond an operator can still be left in difficulty if for non-safety considerations, such as commercial, economic or liability exposure, a DAH decides they do not want to resume the fatigue test (Section 2.4.1). In such a case the only alternative would be to start the test from scratch which, as mentioned earlier, would probably not be economically viable.

As a number of respondents to the NPRM noted, the economic implications of such a requirement have enormous implications for the aircraft re-sale market. First it could drastically reduce the re-sale value of aircraft which up to this point often have had potential for a significant working life in cargo or other roles once their passenger carrying days have been completed. Second, the cost of acquiring converted aircraft would increase substantially as these regulations essentially make operators forever captive to the DAHs, who for non-safety reasons may not be willing to undertake conversions in the first place. Once again, while appreciating that safety is paramount and cannot be compromised, given the economic implications of the proposed regulations it is necessary to consider the following questions:

- Does a Full-Scale Fatigue Test provide the only way of evaluating the WFD characteristics of an aircraft?

- Will the provision of results from a Full-Scale Fatigue test significantly enhance the safety level of the aircraft over and above that provided by current and pending regulations?

These issues can perhaps best be addressed by considering what is achieved by undertaking a Full-Scale Fatigue Test and the significance of the final result that is
obtained. An overview of FSFTs and their significance is presented in Sections 2.4.2.1 and 2.4.2.2.

2.4.2.1 The Significance of Full-Scale Fatigue Tests

Data from a full-scale fatigue test is certainly advantageous as it can provide significant insight into where damage may occur in an aircraft structure. The test itself is based on the application of a usage spectrum, considered to be reasonably representative of the anticipated operational environment, to a structural test specimen, considered to be reasonably representative of operational aircraft structural configurations. Of necessity, a fatigue test encapsulates a number of compromises. For a design validation FSFT used as part of the aircraft certification process, an aircraft OEM will remove an early but structurally representative airframe from the production line and place it in a test rig. Based on a variety of sources of established and projected loads data, a test spectrum will be developed and applied. For a life-extension FSFT a representatively configured aircraft is generally removed from the fleet and subjected to a spectrum which has often been synthesized from operational data obtained via a Structural Health Monitoring (SHM) program and/or limited flight tests. The SHM programs themselves tend to vary significantly with regards to their scope, complexity and duration.

Regardless of whether the fatigue test is a design validation or a life-extension test, practical constraints with regard to the test equipment and control systems mean that the final spectrum that is applied to the test specimen is a compromise that allows the test to run in a realistic timeframe. In such an environment, not all load conditions can be matched exactly. Therefore, the test designer strives to ensure that:

1. stress distributions at all critical locations are matched as closely as possible to those that will be encountered in the actual operational environment; and

2. locations where the stress distributions are not matched are not overloaded during the test such that they are “artificially failed” and the test has to be prematurely terminated.

A FSFT provides one data point which is used to substantiate the design and ongoing airworthiness of an aircraft by keeping the cycles to which it has been subjected ahead of those accumulated by the fleet lead aircraft. This information helps to confirm/set corresponding inspection threshold and repeat intervals. Assuming that a representative load spectrum is applied to the airframe, the fatigue specimen becomes the fleet “high-time” aircraft. Damage that occurs on a test is repaired if it is considered that leaving the damage unattended may result in the test not attaining the test period required to substantiate the desired operational life. As repairs are validated on the fatigue test specimen, so they are introduced into the actual aircraft fleet to ensure that operational failures do not occur prior to the aircraft obtaining their DSG. Data obtained from the
fatigue test may result in structural modifications being introduced into operational aircraft or later production models to ensure that potentially life-limiting problems are avoided all together.

2.4.2.2 Understanding the Load Environment - A Critical Factor

One of the most critical aspects of a FSFT is that of developing a load spectrum that is representative of the load environment an aircraft will encounter during its operational life. It is important to remember that the load spectrum that is applied represents a snapshot of the anticipated environment at the time the test program was finalized. If, over time, the use of the aircraft changes the applicability of the results obtained from a FSFT to fleet aircraft can become questionable. For that reason, the ongoing airworthiness of an aircraft based on the data obtained from a FSFT presumes that the actual operational environment remains consistent with the test environment of the FSFT. This implies an inherent requirement to implement some type of flight monitoring to allow an ongoing assessment of whether the actual loads environment experienced by operational aircraft still falls reasonably within the bounds of the loads applied to the FSFT. If this proves not to be the case, appropriate adjustments have to be made to compensate for the differences in load environment between the FSFT and the actual operational environment.

The loads that are applied to an aircraft structure can change for one of two reasons. The first and most obvious reason for a change in the applied loading results from changing operational requirements. An aircraft is now being used in a role that was not necessarily envisioned when it was originally designed[3]. A good example of this would be the conversion of a civilian aircraft to a low-level role such as aerial firefighting, crop/pollution spraying, ILS/VOR Calibration or maritime surveillance. The low-level environment inherent in these operational roles is particularly severe and can result in “unanticipated” fatigue-induced failures[22].

A second and perhaps more subtle change is when aircraft nominally flying the same mission experience a change in load spectrum over time due to changes in operational and flying technique. Such trends can be harder to catch as many commonly used statistical validation techniques can inadvertently result in the rejection of valid data that actually reflects a real change in usage. Evidence of changes in usage can readily be seen from G-Level Exceedance curves, an example of which is illustrated schematically in Figure 2.

A G-level Exceedance curve looks at the number of exceedances over time of the vertical acceleration at an aircraft’s centre of gravity. For the reasons detailed in Reference [22], such data, while of limited use for quantitative analysis, can nevertheless provide an excellent qualitative indicator of significant changes in operational usage.
As depicted in Figure 2, an individual spectrum consists of a positive and negative component. The relative severity of different spectra, and hence the severity of the stresses at a critical location, can be quickly evaluated by looking at their position on a G-Level Exceedance diagram. The more severe the spectrum, the more its positive and negative components migrate outward from the intersection of the vertical and horizontal axes. Consequently, for the two spectra illustrated in Figure 2, the severity of the red (dashed) spectrum is greater than the green (solid) spectrum.

Figure 3 depicts actual spectra extracted from References [23] and [24] for DC-6 aircraft that were monitored while operating in a low-level firebombing role, a domestic transport (original design) role, a low-level crop dusting (Budworm Spraying) role and a high-level Ferry Role (in transit to crop spraying). Even though relatively little data was gathered for the aircraft operating in the firebombing role[25], it is apparent from Figure 3 that the severity of the spectrum increases as the role changes from domestic/ferry to crop dusting to firebombing.

The gradual change of load spectrum for aircraft operating in nominally the same role is illustrated in Figure 4. The data is obtained from a fleet of four-engine, high wing military transport aircraft. It is evident that the load spectrum that is experienced increases in severity from the mid 1960s to the early 1990s. Such changes in severity can be attributed to changes in operational procedure, mission mix, operational locations etc.
Figure 3: Change in Load Spectrum Due to Change in Role

Figure 4: Change in Load Spectrum in Nominally the Same Role
2.4.2.3 Relevance of a Full-Scale Test Result to WFD Prediction

While having data from a fatigue test is certainly beneficial, as an aircraft ages care must be taken to ensure that a fatigue test that may have been completed some twenty to thirty years earlier using an assumed test spectrum is still representative of the actual operational usage. To a large extent this issue can be resolved if the aircraft involved are participating in a Structural Health Monitoring program. If an ongoing SHM program has not been put in place to a large extent an analyst is “flying blind” when it comes to assessing ongoing aircraft structural integrity[26] [27].

2.4.3 Lack of an Effective Method for Detecting WFD

Part of the justification for the implementation of the current NPRM is that none of the initiatives that are currently implemented under the auspices of the FAA Aging Aircraft Program specifically address WFD. While this is certainly true, both the FAA and the AAWG note that the aging aircraft initiatives do appear to be effective in detecting WFD. This is evidenced by the fact that while WFD has played a role in several safety incidents involving large transport airplanes, there has not yet been a catastrophic accident that can be directly attributable to WFD[1][14]. Even in the Aloha incident that first brought WFD to the attention of aeronautical community, WFD was only cited as a contributory factor to the incident with poor inspection and maintenance procedures being cited as the other contributory factors[15].

2.4.4 Violation of the One-Level of Safety Principle

The need to implement the proposed WFD regulations immediately on large transport category aircraft while exempting regional jets in violation of the FAA’s own “One-Level of Safety Policy”[1][13] is hard to comprehend. There appears to be little to no technical basis for the rationalization the FAA provides for violating the “One-Level of Safety Principle” in the NPRM. If the safety aspects of the proposed NPRM are essential to preserve the integrity of Transport Category aircraft, the NPRM should apply to all Transport category aircraft and not be limited by an arbitrary choice of weight limit.

2.4.5 Definition of Design/Extended Service Goals

The NPRM as it currently stands attempts to define Design/Extended Service Goals for most of the aircraft types that the proposed rule would impact. In a number of instances the validity of these estimates would appear to be at odds with operational experience[9][10][11] even though purportedly the limits were derived “by the type certificate holders or on a conservative estimate by the FAA”[4].

For many older aircraft which were certified prior to FAR 25.571 Amendment 45 and for which a FSFT result is not available, the values included in the NPRM effectively define the IOL for the aircraft. As the time limit for compliance with these requirements is relatively short, aircraft that already exceed the “conservative IOL estimate” would have
to be grounded in fairly short order after the introduction of the proposed rule. Additionally, if the DAHs of the affected aircraft indicate they do not wish to undertake the work to establish a more realistic IOL (Section 2.4.1), the operators would appear to have no way of restoring their aircraft to operational status.

As there may be several areas on an aircraft which can be subject to WFD, the IOL or EOL of an aircraft is defined by the lowest calculated value of the IOL/EOL\(^5\). As noted in the NPRM, IOL/EOLs need to be stated in terms of number of flight hours or flight cycles depending on the structure involved. For example, it is logical to quote an IOL/EOL for a fuselage in terms of a number of cycles as it is primarily the pressurization cycle that will contribute to its fatigue damage. Conversely, for structure such as the wings which typically accumulate fatigue damage due to repeated flight loads over time, it is more logical to define any IOL/EOL in terms of flight hours\(^1\).

Having made the distinction between flight hours and flight cycles, the FAA then proceed to define all the target service goals in the NPRM in terms of flight cycles, without providing any insight with regard to the type of structure to which the limit applies. Based on the preceding argument one could assume that all the critical areas to which the limits apply are primarily related to fuselage structures. The confusion that can be caused by the way the service goals have been specified is already evident from one of the responses to the NPRM. In Reference [27] it is noted that the IOL for the L382 aircraft is 50,000 flight hours based on concerns related to the wing of the aircraft. There is no clear way to determine how, if at all, this is related to the 20,000 flight cycles specified in the NPRM\(^1\).

If the FAA is going to specify a DSG/ESG for operational aircraft in the NPRM, which in the case for many pre FAR25.571 Amendment 45 aircraft will be equivalent to their IOL, they need to be:

1. Consistent with current operational experience; and
2. Denote the area(s) of the structure upon which the limit has been based.

3 ALTERNATE MEANS OF COMPLIANCE

Before considering the mechanism associated with obtaining an Alternate Means of Compliance (AMOC), there is some merit to reflecting on the concerns/intent that has led to the development of the WFD NPRM.

The primary concerns related to WFD appear to be:

1. As aircraft age they will all become susceptible to WFD which essentially is a ‘wearing-out” of their structures due to fatigue;
2. WFD may or may not be detectable prior to the rapid linking of widespread damage. This can lead to an instantaneous critical, if not catastrophic, structural condition where the residual strength of the aircraft is no longer capable of sustaining operational loads;
3. Given the apparent uncertainty associated with the prediction/management of WFD, the regulatory approach that is being proposed is one of ensuring continuing airworthiness through conservative avoidance (i.e. caution based on a “fear of the unknown”).

To address WFD the FAA wish to establish:

- The structural status of all large transport category aircraft (i.e. where they are in relation to their DSG/ESG);
- The point in an aircraft’s life-cycle where WFD can be expected to occur; and
- Analytical/Experimental predictive methods that can be used to determine when inspections should be started and when structure needs to be modified/replaced such that an aircraft can maintain operational airworthiness.

As noted in Section 2.4, the airworthiness consequences associated with the proposed WFD NPRM, particularly for pre FAR 25.571 Amendment 45 certified aircraft, are significant. Given that primarily as a result of current programs implemented under the aging aircraft initiative there have been no catastrophic accidents attributed to WFD\(^{[14]}\), the question arises as to whether the reduction in risk purported to be obtained by the introduction of the proposed regulations is commensurate with the potential economic and socio-economic upheaval? Clearly it is not in the best interests of the industry to become complacent about and/or compromise safety. However, it is also in the interest of both the FAA and the industry to explore whether there might be alternate, more commercially viable, methods of addressing the concerns associated with WFD without compromising the ongoing structural airworthiness of operational aircraft.

One commercially viable alternative is proposed in Sections 3.1 and 3.2. It is based on adopting a pro-active approach to ongoing structural airworthiness through the development of a Strategic Structural Health Management Plan (SSHMP) that is implemented through the judicious use of prognostic and diagnostic structural health monitoring tools.

### 3.1 The Basis for an Alternate Means of Compliance

Alternate Means of Compliance (AMOC) provide a well established concept that can be used within the context of the FAA regulatory environment. AMOCs exist in recognition that Advisory Circulars such as References [3] through [6], define one means, but not the only means of regulatory compliance\(^{[1]}\). Within the context of the proposed NPRM, one AMOC that is of particular interest is compliance through an Equivalent Level of Safety (ELOS) finding. ELOS has been developed to deal with circumstances when direct compliance with regulations is not possible. It provides an exemption from regulations providing the same level of safety to that intended by the regulations can be demonstrated by some other means. Clearly, identifying and demonstrating compensating features that will ensure an equivalent level of safety are a key component of any ELOS submission. An ELOS is generally restricted to situations where no novel or unique design features are introduced\(^{[28]}\). As such an AMOC based
on an ELOS finding has the potential to provide a cost-effective alternative to the current WFD NPRM, particularly for pre FAR25.571 Amendment 45 certified aircraft.

### 3.2 Proposed Approach for a WFD AMOC

The alternate approach proposed is based on utilizing as much fatigue evidence as possible from a variety of sources to establish the current status of an aircraft which is then confirmed through a baseline inspection. Once a baseline has been established, the aircraft is equipped with a structural health monitoring system and a reliable diagnostic tool capable of detecting the presence of small cracks in WFD critical areas. The ongoing information from the SHM system and accompanying diagnostic tool is used to regularly evaluate the actual use of the aircraft and to provide early warning of any potential widespread cracking. The information received allows maintenance, inspection and Structural Modification Points to be adjusted appropriately to accommodate the actual operational environment, while at the same time ensuring that the residual strength characteristics of critical structural areas are capable of sustaining anticipated operational (Limit) loads.

#### 3.2.1 Overview of Strategic Structural Health Management

A key factor that will contribute to the successful implementation and ongoing management of the proposed AMOC is that of having in place a structured approach to isolating and responding to the implications of the structural health monitoring data in timely manner. This capability is necessary to avoid the type of inspection and maintenance oversights which to date appear to have contributed to most WFD incidents, including the Aloha Boeing 737\(^{15}\) incident.

A Strategic Structural Health Management Plan involves the integration of all relevant structural information pertaining to an aircraft fleet(s). It provides a five-year sliding window which allows an operator to identify and respond to WFD and other life-cycle management issues in a timely and proactive manner. The overall process is illustrated in Figure 5.
Among the issues that are addressed in the Strategic Structural Health Management Plan is a Methodology Document that describes the approach that will be used to ensure the ongoing airworthiness of aircraft throughout their operational life-cycle. The methodology document details how WFD will be addressed from an analytical, experimental, inspection and modification perspective. It is worth noting that in “recognition of the importance of ongoing communication and cooperation between applicants and the FAA”[1], there is considerable merit in submitting this document to the FAA for review and approval prior to submitting a Certification Plan; particularly when an ELOS finding is being sought. A Certification Plan inherently assumes a methodology for the demonstration of compliance. If the methodology that underpins the Certification Plan, is not acceptable to the FAA, both they and an applicant may experience significant frustration and expend substantial resources to no avail. The methodology document provides a relatively inexpensive way of resolving all methodology related issues up-front, thereby streamlining the subsequent compliance process. This type of approach has been applied with regard to the certification of aircraft that will be operated in special mission roles such as aerial firefighting.

3.2.2 Establishing a Baseline for Existing Aircraft

Another important aspect related to any proposed AMOC is that of establishing a baseline with regard to the current structural health of the individual aircraft within a fleet. This is particularly important for pre FAR 25.571 Amendment 45 aircraft where there was no requirement for a fatigue test. Records for these aircraft usually only contain statistics related to the number of take-off and landings for the aircraft and the
accumulated flight hours (which may not reflect the hours/cycles for all significant structural components currently fitted to the aircraft).

Figure 6 illustrates the baselining process that, in this instance, was developed for an airtanker operating in the aerial firefighting role.

Regardless of the role, baselining an aircraft usually involves a finite number of distinct phases which include:

1. **Identifying critical structural areas for the aircraft from a durability/damage tolerance and WFD perspective.** This involves a detailed review of, but is not necessarily limited to, the following documents:
   
a. all available structural inspection, maintenance and modification data pertaining to the aircraft;

   b. Service Bulletins, ADs etc.;

   c. Past operational service history; and

   d. Any available OEM and/or DAH engineering/design data including data from any sub-component or full scale fatigue tests.

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Figure 6: Schematic Diagram Illustrating the Baselining Process
Based on this analysis and using guidance material that was developed by groups such as the AAWG[29] and incorporated in FAA Advisory Circulars[5], potential critical structures and details are defined.

2. **Generating a baseline fatigue and damage tolerance analysis for the aircraft based on its design spectrum.** The availability of DAH loads data in this instance is extremely helpful. However, if no such data is available, it is possible to reverse engineer the process with the assistance of sources such as:

   a. the aircraft Type Certificate Data Sheet;

   b. the Certification Criteria to which the aircraft were designed/approved;

   c. any Supplementary Structural Inspection Documents that were generated (Note: quoted values of thresholds and repeat intervals may be hard to match as these values are often conservatively factored down) and;

   d. published aircraft spectrum against which the aircraft was originally designed (e.g. MIL Spec 8886[30] and ESDU Maneuver and Gust Spectra[31][32])

Once a baseline load spectrum has been generated, fatigue and damage tolerance analysis can be undertaken at critical areas using representative material data and geometry factors. The geometry factors themselves can be calculated using either closed-form and/or experimentally/numerically (e.g. finite element) generated solutions.

The data and analysis can be calibrated/confirmed using actual operational service histories of failures determined in the first phase, combined with judiciously selected non-destructive sampling inspections/teardowns at selected locations on operational aircraft. It should be noted that when specifying the required non-destructive inspections/teardowns care should be taken to ensure that the process itself does not introduce damage which can develop into WFD. This can be particularly true of scenarios where the removal and inspection of large numbers of adjacent fasteners are specified. The removal of fasteners that have not been extracted since manufacture can cause localized damage which in turn can become prime sites for fatigue crack initiation and propagation.

Following the development of a valid models and stress spectra for critical locations WFD simulations can be run along the lines of those described by several OEMs and operators in Reference [29]. It should be appreciated that any numerical simulation is only as good as the input data with which it is provided. Therefore some limited coupon test data of representative material specimens (which may not be comprised of virgin material) together with factors that account for geometric scaling may need to be generated[29].

The baselining process should allow a conservative estimate of ISP and SMP values for critical structural locations to be determined and hence preliminary IOL for the aircraft to be defined. Once such a value has been established, the next stage is to implement an ongoing structural health monitoring program to confirm that the actual use of the aircraft stays within the bounds assumed by the
analysis. If this proves not to be the case then the analysis will have to be iteratively adapted to reflect actual usage and the ISP and SMP for each critical area adjusted accordingly. This in turn will impact the IOL of the aircraft. The ongoing process of determining whether actual usage stays within the bounds of assumed usage during the remaining operational life of the aircraft is discussed in Section 3.2.3.

3.2.3 Prognostic/Diagnostic Health and Usage Monitoring

As discussed in Section 3.2.2, once a preliminary IOL has been established for an aircraft, it is necessary to ensure that its operation stays within the bounds of the analysis for the remainder of its operational life. Given the concerns about WFD, there are two aspects that need to be addressed with regard to ongoing monitoring:

1. Confirming and monitoring the operational loads environment in which the aircraft is operating to ensure that it stays within the bounds assumed within the damage tolerance and WFD analysis; and

2. Monitoring critical areas that are considered susceptible to WFD on an ongoing basis to identify as early as practicable any evidence of widespread damage resulting from fatigue.

By coupling these two capabilities it is possible to develop a prognostic/diagnostic capability that provides an invaluable structural health management tool in general and one that is capable of addressing the concerns related to WFD in particular. This is discussed in more detail in Sections 3.2.3.1 and 3.2.3.2

3.2.3.1 Prognostic – Structural Health Monitoring

A typical health monitoring scenario is shown in Figure 7. Geographically dispersed aircraft are equipped with structural health monitoring systems comprised of a recorder and sensors. Data that is obtained from the aircraft is downloaded, validated and transmitted to a central facility where it can be distributed for analysis and review. The process of acquiring, validating, analyzing and managing the data is not a trivial task and to ensure the success of the program it is essential that a number of issues are addressed. Detailed discussions pertaining to the data acquisition and management aspects of structural health monitoring programs can be found in References [33] and [34].

From the engineering perspective there are a number of factors that need to be taken into consideration when implementing an SHM program, particularly for older aircraft for which it may or may not be possible to obtain DAH support.

The first consideration is that of the scope of the program. There are usually a number of Principal Structural Elements (PSEs), each containing a number of critical structural locations which need to be looked at and for which a stress spectrum has to be derived. The instrumentation of all these locations can be prohibitively expensive and therefore a rationale has to be developed with regard to implementing a commercially viable system.
that provides the information required for a realistic damage tolerance/WFD assessment to be undertaken.

Figure 7: A Typical Structural Health Monitoring Scenario

The approach that has been adopted is that of establishing Control Points which can be used as the basis for evaluating large areas of structure. Control Points typically meet one or more of the following guidelines:

1. They coincide with points of measurement previously used on FSFT and/or flight tests to provide some correlation with historically generated data;

2. They confirm boundary conditions that can be used to calibrate/confirm detailed analytical models that will be modified/developed for damage tolerance/WFD analysis. The analytical models themselves can either be numerical models (e.g. Finite Element or Boundary Element) or closed-form solutions such as can be found in References [35], [36], [37], [38] and [39];

3. They provide information that can be leveraged through the use of transfer functions to provide stress distributions at a number of different locations. Appropriate transfer functions are usually generated during the baselining process described in Section 3.2.2.
Using these guidelines it is possible to develop a cost-effective structural health monitoring system that can provide reasonably comprehensive coverage of critical areas of interest using relatively few strain sensors. In addition to monitoring strains directly, a number of common aircraft parameters are also monitored to provide input into transfer functions and also to provide an appropriate context in which the data can be interpreted (i.e. what was the aircraft doing at the time a certain loading situation occurred). To provide further insight into the data, discrete events corresponding to significant phases of the flight may also be monitored. An example of how this method may be implemented in an operational environment can be found in Reference [40].

Data obtained from the structural health monitoring system is compared at regular intervals with the data that was used to baseline the aircraft and predict the preliminary IOL. If the actual operational data appears to lie outside the bounds (i.e. is more severe) of that used to predict the original IOL, a revised analysis is undertaken and a modified IOL determined. Inspection and maintenance intervals can then be adjusted accordingly. It should be noted that assuming there was a reasonable correlation between historic damage sustained by the aircraft and the predicted damage using the reconstructed spectrum (Section 3.2.2), the new spectrum that is generated should only be used for the analysis of current and future flying.

The frequent analysis of the data gathered from the Structural Health Monitoring system and, if appropriate, its use to refine IOL values, provides a predictive capability with regard to the anticipated timeframe that WFD can be expected. In turn, this defines an IOL for the aircraft that is based on actual as opposed to assumed operational usage.

### 3.2.3.2 Diagnostic - Comparative Vacuum Monitoring Technology

One of the major concerns about WFD is that prior to it being detected structural failure will occur as a result of the residual strength of a structure being degraded to the point where normal flight loads can no longer be sustained. From an NDI perspective the isolation of WFD is certainly challenging as relatively small cracks have to be detected in a timely manner. Even though the programs that have been put in place under the auspices of the FAA’s Aging Aircraft initiative [41] (Section 2.2) have been reasonably effective in assisting with the detection of WFD[14], there still appears to be a level of discomfort with respect to whether WFD can be identified prior to it becoming critical.

The early identification of WFD is particularly important with regard to any AMOC based on an ELOS, as proposed in this paper. A capability to detect WFD at an early stage provides an additional level of back-up that:

1. Initially helps to mitigate the risk of failure occurring prior to enough operational data being gathered to substantiate/modify the assumptions used in the generation of a preliminary IOL (Section 3.2.2); and

2. Over the longer term manages risk by alerting operators to the presence of WFD so that appropriate and timely actions can be implemented prior to an unacceptable degradation of structural residual strength being attained.
Recent advances in NDI technology show some promise with regard to the ongoing monitoring and/or early detection of WFD. Of particular interest is Comparative Vacuum Monitoring (CVM) technology which potentially offers a relatively inexpensive yet reliable method of WFD detection. An overview of CVM Technology is presented in Section 3.2.3.3. A more detailed discussion with respect to its potential application(s) to detecting WFD is presented in Section 3.2.3.4

3.2.3.3 An Overview of CVM Technology

The principle on which CVM is based is illustrated in Figure 8.

Figure 8: Schematic Diagram of CVM Principle

CVM works on the principle that a steady state vacuum maintained within a small volume is sensitive to any leakage. CVM sensors are general made of an elastomeric material and consist of alternating channels of air and vacuum. However integral sensors which can be embedded in components have been developed and are currently being evaluated.

External sensors are adhesively bonded to either metallic or composite structure which forms one part of the vacuum manifold. As a crack initiates and starts to propagate under the sensor, a leakage path between adjacent vacuum and air channels is formed. This leakage is sensed by a monitoring device which can then alert an operator to the presence of a crack. The method has been shown to be quite sensitive and in certain practical applications has detected cracks of the order of 250μm (0.010”).

A typical installation on a C-130 Rainbow Fitting is illustrated in Figure 9. The external sensors are relatively small and can be manufactured to address quite complex geometries. Typical surface preparation required to attach the CVM sensors to a surface is similar to that required for the installation of strain gauges.
A CVM system is comprised of three primary components as illustrated in Figure 10.

The components are:
• The Sensor which can be conformed to shaped surfaces and to cover fasteners
  (Note: As shown in Figure 9, the sensor can be made translucent so it is still
  possible to view the underlying structure);

• A fluid flow meter; and

• A stable source of low vacuum.

The fluid flow meter and a stable source of vacuum have been integrated into a portable
piece of ground support equipment which can be easily used by maintenance personnel.

CVM sensors can be applied individually at critical locations or coupled in larger groups
to provide large area coverage. To date, they have been applied to or are in the process
of being accepted for:

• Airbus A380 FSFT and the A320 Flight Test Aircraft;

• The Boeing NDI Standard Practice Manual. It is anticipated that in 2007 CVM
  sensors will be offered by Boeing as AMOCs capable of addressing several
  Boeing Service Bulletins;

• C-130 Aircraft, P-3 Aircraft, A4-SU and S-211 Aircraft; and

• Black Hawk, Sea-King and CH-53 Helicopters

3.2.3.4 CVM WFD Applications

Currently, optimal results from CVM externally applied gauges are obtained when they
are applied to thinner structures where surface or through cracks occur. Fortunately,
this covers many of the areas in which WFD has so far been encountered. Ongoing
research is looking at the use of CVM embedded gauges to deal with more complex
and/or thicker structure where cracks may tend to tunnel. It is anticipated that an
increasing number of solutions for thicker structures will become available over the next
few years.

Following the identification of WFD critical areas in accordance with the procedures
described in Section 3.2.2, CVM gauges will be installed at critical locations. Given that
by its very nature, the exact sequence of WFD linkage can be hard to predict, the
majority of installations will probably be based on coupling a number of CVM gauges in
critical areas to provide broad area coverage. In some instances, individual CVM
gauges would be used to provide a more focused assessment of the exact location of
the damage. Regular readings of the gauges would be stored together with data
obtained from the associated Structural Health Monitoring system.

Based on its current state of development, it is anticipated that CVM monitoring for WFD
will be implemented in two phases:

• **Phase 1:** During this phase the system will be implemented in its present
  configuration which allows tests to be performed by ground crew on a regular
basis at each critical location during regular service/maintenance operations (Note: the speed at which the inspection can be completed allows an inspection after each flight if required). Once the CVM Sensor data is obtained it will be evaluated by maintenance personnel and forwarded to a central location for final data validation and integration with data obtained from the structural health monitoring system;

- **Phase 2**: The CVM gauges that have been installed will be integrated with a revised configuration that integrates CVM system with the Structural Health Monitoring system to provide in-flight monitoring. There are a number of advantages associated with moving to in-flight monitoring. These include easier data integration and better resolution. The improved resolution is a consequence of cracks at some locations opening-up under load and giving an earlier indication of their existence.

### 4 CONCLUSIONS

Over the past eighteen years, the Aloha Airlines Boeing 737 failure has resulted in the identification of Widespread Fatigue Damage as a significant issue with regard to maintaining the continuing structural airworthiness of aging aircraft. Although subsequent WFD incidents have occurred, as a result of aging aircraft initiatives that have been implemented by the FAA no single incident/accident attributed directly and solely to WFD has yet occurred. However, as safety cannot be compromised and complacency with regard to safety must be avoided, the FAA in collaboration with industry has sought to integrate WFD criteria into the certification/approval and ongoing airworthiness process. In this regard, the FAA issued an NPRM related to WFD in April 2006.

While few if any of the many respondents to the NPRM disagree with the need to identify and manage WFD, grave concerns have been expressed about the proposed method of implementation which is focused around obtaining data from an FSFT. For pre-FAR 25.571 Amendment 45 (damage tolerance) certified aircraft, such a requirement will have significant operational consequences as FSFTs were generally not undertaken since there was no regulatory requirement for such a test. As many aircraft in this category are approaching the later stages of their life-cycle, the economic viability of undertaking a FSFT is at best marginal. Consequently many viable aircraft could be grounded even though they have yet to exhibit any signs of WFD.

Even for post-FAR 25.571 Amendment 45 aircraft the regulations in their current format could have significant consequences. For example, no guidance has been provided with regard as to how to meet the proposed regulations if the DAH decides not to pursue the establishment/extension of an IOL/EOL for either technical or commercial considerations. This could severely limit the aircraft conversion industry.

An Alternate Method of Compliance (AMOC) for addressing WFD based on demonstrating an Equivalent Level of Safety (ELOS) to the pending regulations has been proposed. The alternate approach is based on utilizing as much fatigue evidence as possible from a variety of sources to establish the current status of an aircraft which is confirmed through a baseline inspection. Once a baseline has been established, the
aircraft is instrumented with a structural health monitoring system that is coupled with a
diagnostic tool capable of reliably detecting the presence of small cracks in WFD critical
locations prior to them becoming critical. The AMOC would couple the prognostic
capabilities afforded by modern Structural Health Monitoring systems with the diagnostic
capabilities of Comparative Vacuum Monitoring. This combination provides a powerful
prognostic/diagnostic tool that allows WFD to be managed in a safe and economic
manner over the life-cycle of an aircraft.
5 REFERENCES


4. “Continuing Structural Integrity Program for Large Transport Category Airplanes (Draft 9)”, FAA Advisory Circular AC 91-56BX, 1 April, 2002.

5. “Widespread Fatigue Damage on Metallic Structure (DRAFT)”, FAA Advisory Circular AC 120-YY.


