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Development, Validation, and Demonstration of Health and Usage Monitoring System Technology to Detect Rotorcraft Mechanical Faults

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Final Report

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16. Abstract

This report presents the results of the work performed by GE Aviation and Sikorsky Aircraft Corporation. The goal of this work was to demonstrate the ability of both traditional and advanced Health and Usage Monitoring System (HUMS) technologies to detect rotorcraft mechanical faults, and to research the validation of HUMS for a Condition-Based Maintenance (CBM) credit in accordance with the requirements of Advisory Circular (AC) 29-2C Section Miscellaneous Guidance (MG)-15.

A key element was to demonstrate and validate the ability of HUMS algorithms and methodologies to detect incipient mechanical faults and facilitate timely maintenance intervention. The work was focused on the application of vibration health-monitoring techniques to the S-92A® oil cooler bearings (OCB). A comprehensive analysis of both the S-92A oil cooler fleet bearing HUMS fleet data and rig test data acquired during this research was used to generate direct evidence for the OCB CBM credit validation. The analysis extended beyond the requirements for maintenance credit validation to include (1) a wider assessment of bearing monitoring capabilities and (2) how these could be optimized to provide the greatest CBM credit potential. The results confirmed that the bearing monitoring system can detect a range of bearing faults before they reach a critical condition.

The research showed that the bearing monitoring system has the potential to provide the target OCB CBM credit. Therefore, credit application could be made in accordance with MG-15, based on supporting plans for the introduction to service and continued airworthiness that were generated. During this research, the OCB time between overhauls was actually extended from 2500 to 3500 hours using the traditional lead the fleet-based approach. As an additional input to the research, the process that was invoked to obtain the time between the overhaul extension was compared to the requirements of MG-15. It was shown that there was considerable synergy between the lead the fleet-based approach and the requirements of MG-15, and that the process that was already performed would satisfy many of the key MG-15 requirements.

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LIST OF ACRONYMS

AAD	Advanced anomaly detection
AC	Advisory Circular
ADS	Aeronautical Design Standard
AED	Aviation Engineering Directorate
AGB	Accessory gearbox
AMC	Acceptable means of compliance
AMM	Aircraft Maintenance Manual
AWL	Airworthiness limitations
BMS	Bearing Monitoring System
CBM	Condition-Based Maintenance
CG	Cage
CI	Condition indicator
CIS	Controlled Introduction to Service
COTS	Commercial off-the-shelf
CRC	Cyclic redundancy check
DI	Detection index
DoD	Department of Defense
DTU	Data transfer unit
E&AM	Engineering and Asset Management
EASA	European Aviation Safety Agency
EI	Energy index
EL	Rolling elements
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FFT	Fast Fourier Transform
FHA	Failure Hazard Assessment
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes Effects and Criticality Analysis
FOD	Foreign object damage
FRACAS	Failure Reporting, Analysis, and Corrective Actions System
g	Acceleration due to gravity
GenHUMS	Generic HUMS
GSS	Ground support station
HI	Health indicator
HP	High pass
HUMS	Health and Usage Monitoring System
ICA	Instructions for Continued Airworthiness
IGB	Intermediate gearbox
IN	Inner race
JAR	Joint Aviation Requirements
LP	Low pass
LTF	Lead the fleet
MFD	Multifunction display
MG	Miscellaneous Guidance
MG-15	Advisory Circular 29-2C MG-15

MGB	Main gearbox
MRF	Multiple redundant fasteners
MTBR	Mean time between replacements
MUD	Memory unit download
NPA	Notice of Proposed Amendment
OCB	Oil cooler bearing
OEM	Original equipment manufacturer
OU	Outer race
PA	Probability of anomaly
PB	Passband
PCMCIA	Personal Computer Memory Card Interface Adaptor
Pfa	Probability of false alerts
POD	Probability of detection
R&M	Reliability and maintenance
R&O	Repair and overhaul
RDF	Raw data file
RTB	Rotor track and balance
SAC	Sikorsky Aircraft Corporation
SO	Shaft order
TBO	Time between overhauls
TDS	Tail rotor drive shaft
TGB	Tail rotor gearbox
UBM	Usage-based maintenance
VHM	Vibration Health Monitoring

EXECUTIVE SUMMARY

GE Aviation Systems, LLC and Sikorsky Aircraft Corporation researched the end-to-end process for approving an example Health and Usage Monitoring System (HUMS) Condition-Based Maintenance (CBM) credit in accordance with the requirements of Federal Aviation Administration (FAA) Advisory Circular 29-2C Miscellaneous Guidance (MG)-15, herein referred to as MG-15. The primary target CBM credit was selected in the first year of the program. This was an extension of a 2500-hour time between overhaul on the oil cooler for the Sikorsky S-92A® helicopter, which, in turn, requires an extension of the replacement interval for the oil cooler bearings (OCB). The highest level of criticality of the credit has been identified as "Major."

A key element of this research was to demonstrate and validate the ability of HUMS algorithms and methodologies to detect incipient mechanical faults and facilitate timely maintenance intervention. The work was focused on the application of vibration health-monitoring techniques to the S-92A OCB. A comprehensive analysis of both the S-92A fleet OCB HUMS data and rig test data acquired during the research was used to generate direct evidence for the OCB CBM credit validation. The analysis extended beyond the requirements for credit validation to (1) include a wider assessment of bearing monitoring capabilities and (2) how these could be optimized to provide the greatest CBM credit potential. The results confirmed that the bearing monitoring system can detect a range of bearing faults before they reach a critical condition.

The research showed that the bearing monitoring system has the potential to provide the target OCB CBM credit. Therefore, credit application could be made in accordance with MG-15, based on supporting plans for the introduction to service and continued airworthiness that were generated. During this research, the OCB time between overhauls was actually extended from 2500 to 3500 hours using the traditional lead the fleet-based approach. As an additional input to the research, the process that was invoked to obtain the time between the overhaul extension was compared to the requirements of MG-15. The comparison revealed that there was considerable synergy between the lead the fleet-based approach and the requirements of MG-15, and the process that was already performed satisfied many of the key MG-15 requirements.

This research showed that the practicality and usability of MG-15 contained well-founded material that remains applicable to the certification of HUMS CBM credits. Therefore, while some content of MG-15 could be improved, it does not need to be fundamentally changed or replaced with alternative material. Suggestions have been made to improve MG-15 or to develop additional guidance material. It was recommended that the FAA establish an industry CBM working group, possibly through the American Helicopter Society, to recommend agreed upon refinement to MG-15. It was recommended that such a CBM working group build on the results of this and other FAA-funded research and development and provide more specific guidance for viable approaches to comply with MG-15 for different types of credits. This should eliminate current issues associated with different interpretations of the MG-15 material.

1. INTRODUCTION.

Rotorcraft Health and Usage Monitoring Systems (HUMS) provide a range of functions including rotor track and balance, exceedance monitoring, structural usage monitoring, and engine and drive train Vibration Health Monitoring (VHM) to detect incipient mechanical faults and avoid mechanical failures. A HUMS typically consists of a variety of onboard sensors, a data acquisition and processing unit, and a ground-based system. The acquired data may be processed onboard the aircraft or on a ground-based system, thereby providing the means to measure against defined criteria and generate instructions for the maintenance staff and flight crew for maintenance intervention.

HUMS have been in service since the early 1990s. Initially, these systems were fitted to provide a safety benefit through early detection of mechanical faults and were not intended to fundamentally modify the maintenance schedule or lifing of components. The degree of qualification required for this type of installation is relatively low since the HUMS was certified on the basis of being optional equipment in which the data was used for advisory purposes only.

Driven by increasing demands for safety improvement and operational cost reduction and the availability of new enabling technologies, new HUMS applications are emerging. There is an increasing desire to use HUMS to support Condition-Based Maintenance (CBM), operating cost reduction, and damage tolerance approaches. This type of application requires a higher degree of qualification commensurate to the criticality of the most severe effect of the intervention actions on the rotorcraft. Furthermore, the adoption of CBM must be supported by the certification process, as this is an example of a maintenance credit, defined as: "To give approval to a HUMS application that adds to, replaces, or intervenes in industry-accepted maintenance practices or flight operations." Federal Aviation Administration (FAA) Advisory Circular (AC) 29-2C Section Miscellaneous Guidance (MG)-15 [1], herein referred to as MG-15, requires that any HUMS applications for which maintenance credits are sought must be validated. The primary goal of this FAA-funded research program is to study the end-to-end CBM credit approval process according to the requirements of MG-15.

A key element of the maintenance credit approval process is the demonstration and validation of HUMS algorithms and methodologies to detect incipient mechanical faults and facilitate timely maintenance intervention. Clearly, this implies a need to identify and develop the most effective HUMS mechanical fault detection algorithms and techniques. The secondary goal of the research is to develop, demonstrate, and validate HUMS algorithms and methodologies to support the CBM credit approval process, with a focus on mechanical diagnostics based on VHM technology.

The target HUMS CBM credit for this research was the extension or elimination of the oil cooler time between overhauls (TBO) on the Sikorsky Aircraft Corporation (SAC) S-92® helicopter, which, in turn, required extension or elimination of the replacement interval for the oil cooler bearings (OCB).

Section 2 of this report presents a generic analysis of the CBM credit potential of HUMS. Section 3 describes the selection of the rotorcraft component and credit for the CBM credit validation research. MG-15 is introduced in section 4, and section 5 presents a definition of the

target CBM credit criticality and validation requirements. Section 6 describes the acquisition and analysis of S-92 oil cooler in-service and rig test data for credit validation. Section 7 discusses the feasibility of the target CBM credit on the S-92 oil cooler and describes TBO extensions that are already in use on the S-92 and Sikorsky UH-60 Black Hawk oil coolers. The research results for the end-to-end CBM credit approval process, in accordance with MG-15, are presented in section 8, and section 9 presents the conclusions from the work.

2. GENERIC ANALYSIS OF HUMS CBM CREDIT POTENTIAL.

MG-15 defines a maintenance credit as: "to give approval to a HUMS application that adds to, replaces, or intervenes in industry-accepted maintenance practices or flight operations" [1]. This section reviews the current credit status of in-service HUMS, presents examples of HUMS in-service experience that indicate the future credit potential of these systems, and analyzes a series of different types of candidate CBM credit. This provides useful generic information on the CBM credit potential of HUMS, as well as background information for the selection of the CBM credit that is the subject of this FAA research. The focus of this work is on HUMS mechanical diagnostic functions, rather than usage monitoring functions; therefore, the analysis considers only the CBM credit potential of HUMS mechanical diagnostics.

2.1 CURRENT HUMS CREDIT STATUS.

In-service HUMS have achieved some simple maintenance credits in areas such as

- the use of HUMS data for exceedance monitoring (i.e., gearbox torques and engine turbine temperatures).
- the elimination of dedicated rotor track and balance (RTB) test flights by making limited RTB adjustments based on data from commercial flights.
- the use of HUMS for monitoring high-speed shaft balance.

An Airworthiness Directive was previously approved to extend the TBO for the UH-60 OCB from 2500 to 3240 flight hours for aircraft that are outfitted with HUMS. Vibration thresholds were established through examination of fleet data and limited seeded fault testing.

2.2 EXAMPLES OF IN-SERVICE HUMS EXPERIENCE TO ILLUSTRATE CREDIT POTENTIAL OF MECHANICAL DIAGNOSTICS.

The following are examples of in-service HUMS mechanical diagnostics experience that, although no case had any formal maintenance credit awarded, illustrate a potential for credit.

2.2.1 Example 1: HUMS Detection of Accessory Gearbox Defects on Super Pumas.

Operators of Super Puma Mk2 aircraft equipped with HUMS have used the system to detect defects in accessory gearboxes (AGB). In the past, there were a number of repeat occurrences of a particular defect type within the AGB that resulted in gearbox rejections before the TBO limit was reached. Through this in-service experience, it was possible to demonstrate that the HUMS

mechanical diagnostics function could reliably detect changing vibration characteristics associated with the defect; therefore the HUMS data were used to determine when gearboxes should be rejected. The AGBs could be considered to be operating on-condition for this particular defect mode.

2.2.2 Example 2: HUMS-Based Fleetwide Health Check on Military CH-47Ds.

Soon after the introduction of HUMS on a military Boeing CH-47D Chinook fleet, an aircraft with a newly fitted HUMS suffered the breakup of a combiner transmission bearing. The bearing failure was detected by a chip detector because no mechanical diagnostics threshold was set in the HUMS. However, the system was recording raw transmission vibration data. The raw HUMS data from that aircraft were evaluated and a failure characteristic was identified. It became apparent from the data that bearing spalling had initiated at least 95 hours prior to the overload failure. The failure vibration characteristic was then used to perform a fleetwide health check, and all other HUMS-embodied aircraft were screened within 12 hours. The screening established that no other transmissions displayed similar failure characteristics, thus, allowing the HUMS-embodied aircraft to remain available for operations. It was necessary for the non-HUMS aircraft to be fitted with dedicated vibration sensors every 25 hours to check the combiner transmission bearing until HUMS was fitted.

If HUMS was not installed on the aircraft with the failed transmission, it would not have been possible to identify the failure vibration characteristic. Therefore, to ensure airworthiness, the only option available to the engineers was to ground the fleet and remove, inspect, and replace all combiner transmissions. Again, for a single failure mode that would be detectable on an in-service aircraft, it would be possible to award the HUMS a one-time maintenance credit for that particular failure mode—in this case, preventing a fleet-grounding for gearbox removal and inspection for a particular bearing failure mode.

2.2.3 Example 3: HUMS-Based Bearing Servicing on Super Pumas.

HUMS operators have experienced cases of rising trends in the vibration energy level indicators on the tail drive shaft bearings of Super Puma Mk2 aircraft. Because the accelerometers are close to the bearings, they are sensitive to the bearing condition and the state of the grease lubrication. On the first occurrence, an inspection of the affected bearings was performed and no visible defects were found. Greasing was then performed and the energy levels of the indicators returned to normal. Repeating greasing cycles created a sawtooth trend, with progressive increases in vibration followed by step decreases. The rising HUMS vibration trend could be used to indicate when bearing regreasing is required.

2.2.4 Example 4: Possibility of Combining Chip Detector and VHM Information in Determining Rejection Criteria.

A HUMS operator experienced a small chip on the magnetic plug of a Super Puma main gearbox (MGB). At that point, a HUMS condition indicator (CI) for an MGB gear began to rise. The MGB was left in service and monitored closely by the manufacturer to verify the CI trend. The MGB was subsequently removed after 200 operating hours when a large chip was found on the magnetic plug. This case verified the results of a seeded fault test performed by the

manufacturer in its MGB test cell, confirming that the HUMS could detect a potential defect and monitor the airworthiness of the part while in service. It also indicated the possibility of combining a chip detector and HUMS mechanical diagnostics information to determine rejection criteria. It is not known whether, in this case, the initial small chip originated from the gear generating the rising CI values. It may be difficult to fuse the two sources of information if there is no metallurgical information to indicate the possible source of a chip.

2.2.5 Example 5: HUMS-Based Component Inspection on a S-76® MGB.

A HUMS operator experienced a slow, upward trend on a health indicator (HI) for one of the pinions driving the MGB bull gear on a Sikorsky S-76 aircraft over a period of approximately 800 hours, which eventually crossed the monitoring threshold. On the bull gear, two other indicators showed an upward trend over this period. A borescope inspection of the gears was performed and revealed that the pinion and bull gear had an abnormal tooth wear pattern. In one location, the tooth crown of the pinion gear came into contact with the root radius of the bull gear, creating a marked wear on both faces of the tooth rather than just on the normal load transfer region on the driving face of the tooth. The MGB was rejected and returned to SAC, which subsequently confirmed nonconforming dimensions for gear shaft runout and the profiles and pitch of several teeth. This example shows the potential for integrating HUMS mechanical diagnostic information with established aircraft maintenance procedures; in this case, using the HUMS to direct a targeted (borescope) component inspection.

2.2.6 Summary.

The examples from HUMS in-service experience show that HUMS mechanical diagnostics have the potential to provide CBM credits. They also suggest that the realization of this potential can be most straightforwardly achieved in cases where

- only a limited number of specific failure modes are involved.
- there is direct evidence from in-service experience of the HUMS mechanical diagnostics ability to reliably detect these failure modes in a timely and unambiguous manner.

2.3 CANDIDATE CBM CREDITS FOR HUMS MECHANICAL DIAGNOSTICS.

Using the information in sections 2.1 and 2.2, along with an engineering analysis of the requirements for different types of HUMS CBM credit, it was possible to assess candidate HUMS CBM credits for the FAA research program.

2.3.1 Elimination or Extension of Gearbox TBOs.

Individual manufacturers decide whether gearbox TBOs are required; however, a significant determining factor appears to be whether helicopter types are on the civil or military register. This is due to a combination of different regulatory environments and what can be an order of magnitude difference in flying rates on typical civil and military operations. For example, on Boeing CH-47D Chinooks operated by the U.S. Army, the drive system is on-condition (without HUMS); however, the Royal Air Force imposes its own TBO limits. The manufacturer's rationale for this is that the only failure modes with hazard functions that increase with time are

those that can be reliably detected by traditional means, such as indicating debris screens and chip detectors. In contrast, on civil helicopters (such as the Super Puma), the MGB, intermediate gearbox (IGB), and tail rotor gearbox (TGB) all have TBOs.

For SAC products (S-76 and S-92), which serve as representative aircraft and the primary focus of this research, the situation is also mixed, as shown in table 1. The S-76 has finite TBOs placed on all the primary drive train components. These TBOs were established by a long operational history and are based on fleet reliability data. The components could be placed on-condition, but the only means of detecting the condition with respect to key faults for aircraft without HUMS (i.e., for most S-76 aircraft because HUMS is not part of the baseline aircraft configuration) would be chip detectors. Such an indication to the typical, small commercial S-76 operators, is a significant inconvenience since drive train component removal and repair would be unscheduled, which would negatively impact aircraft availability. The specified drive train component TBOs allow the operator to schedule these maintenance actions. While the lowest bearing life for each component was a key driver for the established TBO, there are a number of other drivers, such as corrosion and gearbox housing life, that also are important. Thus, HUMS would not necessarily eliminate S-76 drive train component TBOs or inspections. However, HUMS would help the operator better schedule maintenance actions, if the maintenance manuals were to be rewritten to allow condition-based or on-condition maintenance protocols. Due to the long operational history of the S-76, the average TBOs would most likely be similar to the specified TBOs currently invoked if the components were to go on-condition. The transition of the maintenance manuals for the S-76 drive train to on-condition or to adopt CBM is extremely unlikely for legacy S-76 aircraft because transitional costs would be significant, the benefit would most likely be low, and most legacy S-76 aircraft do not have HUMS.

Table 1. Comparison of Maintenance Requirements for S-76 and S-92

	S-76 Aircraft			S-92 Aircraft		
Component	Inspection Times (hr)	Replace	TBO (hr)	Inspection Times (hr)	Replace	TBO (hr)
Drive train						
MGB	100, 300, and 1500		3250	50, 500, and 1250		6000
IGB	1500		4500	250 and 1250		
TGB	50, 100, 500, and 1500		4000	50, 250, and 1250		
Oil cooler blower	25, 100, and 300		3000	50, 250, 500, and 1250	9000	
OCB					2500/ 5 years	
Tail drive shaft bearing support assembly	100		3000/ 5 years	50, 250, and 1250	2500/ 5 years	

The S-92 has a specified TBO only for the MGB, and finite replacement times for several drive train components (i.e., tail rotor drive shaft (TDS) hangar bearings, OCB, and oil cooler blower. Note: the replacement interval for the OCBs has been increased via traditional methods to 3500 hours). Everything else is on-condition based on periodic inspections, oil chip detectors and screens, and HUMS vibration and temperature data. The on-condition nature of the IGB and TGB maintenance practices is based on infinite life design, UH-60 on-condition experience, qualification tests, and lead the fleet (LTF) substantiation. It should be noted that HUMS only provides an extra layer of protection and is not required to support the on-condition nature of the design. The component selection analysis for the HUMS CBM credit in section 3.2 includes the IGB and TGB in the list of candidate components because the analysis is meant to be somewhat generic and not specific to S-92 and this research.

As significant fleetwide reliability data are collected for this relatively new aircraft and reliability drivers are mitigated through engineering design changes the MGB TBO is likely to be increased as required. The routine collection of HUMS data for all S-92 aircraft may facilitate this process, but the use of HUMS to achieve a significant maintenance credit for the S-92 MGB is beyond the scope of this effort due to the complexity of the S-92 planetary gearbox. For comparison, the UH-60 drive train, which is quite similar to the S-92 and for which there is a large experience base, is entirely on-condition with the exception of finite replacement times for TDS hangar bearings and the oil cooler.

If HUMS can provide reliable and timely detection of all the failure modes, which are currently controlled by the routine overhaul procedure, gearboxes could be run on-condition. However, it can be argued that there are a number of defect modes for which practical monitoring methods have yet to be proven. Therefore, the goal of using HUMS data to eliminate a TBO for a MGB would be very difficult to achieve. However, the IGB and TGB are much simpler gearboxes. Therefore, a combination of a chip detector and HUMS vibration-based gear and bearing mechanical diagnostic techniques could enable the elimination of an IGB or TGB TBO limit, provided this was supported by in-service gearbox reliability data, and provided other failure or degradation mechanisms, such as corrosion or housing loads, do not drive the TBO.

Gearbox TBO extensions are currently based on reliability information, and performed on a certain number of gearboxes examined at the end of overhaul life and when no undetected defect modes have been revealed that could affect airworthiness. In theory, if a TBO extension is limited by a small number of defect modes, and some can be reliably detected with HUMS while others can be designed out, then the HUMS could be awarded maintenance credit to allow the TBO extension to be introduced (possibly in combination with the introduction of some component modifications).

For a single defect, another scenario can be defined in which HUMS could be awarded maintenance credit relating to the growth of the MGB TBO period. It is realistic to assume that, over the life of an aircraft, new defect modes will be encountered that are not reliably detectable by traditional (i.e., non-HUMS) monitoring processes. This is most probable when extending the TBO in the early and mid-phases of the aircraft life. In the event that such a defect mode is encountered, without HUMS, a decision has to be made as to whether to implement a modification so the problem is eliminated or whether to operate the aircraft over the remainder of

its life with a limited overhaul period on the transmission. A decision to implement a modification still has its setbacks, because this can take several years to design and incorporate. However, if the problem defect mode can be reliably detected by HUMS, then the gearboxes could continue to operate on-condition for that particular defect, and the remaining defect modes will still be covered by the extended TBO. This is a potentially achievable maintenance credit scenario, as the HUMS only has to be validated for one defect mode and, assuming HUMS was already fitted on the aircraft, in-service experience should be available to support the validation process. Although this could be considered a feasible scenario, it is not appropriate for the FAA research program, because it would be only applicable to one aircraft-specific defect mode, and therefore is not sufficiently generic.

In summary, in the short term, it is unlikely feasible to eliminate or extend an MGB TBO on the basis of HUMS mechanical diagnostics alone but, as mentioned previously, this is possible for an IGB or TGB. However, SAC S-76 and S-92 gearbox TBOs, if existent, are not driven by bearing or gear defects.

2.3.2 Elimination or Extension of Other Component TBOs.

The elimination or extension of a TBO on a simpler assembly, such as an oil cooler fan (e.g., for bearing replacement), represents a simpler target CBM credit for HUMS mechanical diagnostics because

- there are fewer potential defect modes to be detected.
- it is easier to perform vibration monitoring of externally mounted bearings than of bearings located within a gearbox, where there are adjacent gears that provide stronger sources of vibration.
- the hazard level associated with an oil cooler fan bearing failure is lower than that associated with the failure of a gearbox bearing in the main drive train.

2.3.3 Elimination of Component Inspections or the Extension of Inspection Periods.

For external components, such as TDS and swash plates, periodic visual inspections are required to ensure continued airworthiness. If a HUMS mechanical diagnostic function can reliably monitor the targeted inspection defect modes, then it may be possible to eliminate the inspection or extend the inspection period. However, a number of items can be checked on inspection; for example, checking the condition of dynamic components, such as shafts and bearings, and checking static components, such as pipes or cables, for signs of chafing. In this case, it is unlikely that HUMS mechanical diagnostics can monitor all the potential defect modes; therefore, the potential for eliminating the inspection is limited. For more targeted inspections, such as a swash plate bearing inspection, there is greater scope for achieving a HUMS credit.

2.3.4 Condition-Based Component Servicing.

HUMS data can be used to determine when component servicing is required, for example, the greasing of TDS bearings.

2.3.5 Modification of Responses to Traditional Indicators.

Although traditional HIs, such as chip detectors mounted in the oil system, have proved to be effective detectors of damage to oil-washed components, their output is limited to a binary state. This creates difficulties for the definition of responses to indications, such as the detection of metallic debris. The result can be a significant disruption to operations (e.g., when the required action is to land the aircraft as soon as possible) and to maintenance schedules. In theory, where HUMS vibration-based mechanical diagnostics provide an additional monitoring capability, consideration could be given to modifying the required response to an indication from a chip detector. However, in practice, there are a number of significant difficulties with this idea. It is unlikely that the source of any metallic debris can be identified without a detailed metallurgical analysis; therefore, it would be difficult to seek confirming health information from vibration data. Oil debris monitoring and vibration monitoring are generally considered complementary functions, because the defect modes that they most effectively detect differ. This type of HUMS credit is not considered to be within the scope of this research, which is focusing on credits based on traditional HUMS vibration monitoring and mechanical diagnostics without the need for additional or advanced sensors.

3. SELECTION OF ROTORCRAFT COMPONENT AND CREDIT FOR CBM CREDIT VALIDATION RESEARCH.

This section summarizes the results of the effort to select the rotorcraft component and CBM credit for this research. The selection process considered information from a number of sources for the S-76, S-92, and UH-60 aircraft, including detailed drive train documentation, such as design, structural substantiation, and failure modes and effects analysis (FMEA) reports; repair and overhaul (R&O) and reliability and maintenance (R&M) databases; and commercial operator experience and opinions obtained through informal discussions (which were less beneficial than expected since commercial operators tend to have small fleets and rely heavily on the original equipment manufacturer (OEM).

3.1 AIRCRAFT SELECTION.

All three SAC aircraft (the S-76, S-92, and UH-60) were considered potential candidates for the focal point of this research. The commercial aircraft were more appropriate candidates due to their being certified under FAA regulations. The S-92 helicopter, shown in figure 1, was selected as the ideal aircraft for this research, because it is based on state-of-the-art structural design practices, incorporates a sophisticated HUMS in the baseline aircraft configuration, and has CBM potential due to SAC's ultimate goal to put key drive train elements on-condition. Also, as part of the S-92 controlled introduction to service (CIS) plan, an S-92 LTF program was initiated to support the validation of current TBOs and on-condition maintenance criteria for key drive train components. The S-92 HUMS data was continuously gathered for all aircraft in the fleet, including the LTF aircraft. This provided a unique opportunity to cost effectively gather both HUMS and teardown and inspection data to compare HUMS condition indices with component condition.

Figure 1. The S-92 Aircraft

The primary disadvantage of selecting the S-92 is the fairly limited amount of operational, R&O, and R&M data for this relatively new aircraft compared to the S-76. However, the advantages of using the S-92 aircraft as the focal point clearly outweighed the one disadvantage, which is mitigated by the fact that real-time HUMS data has been continuously collected and incorporated into a SAC web-based server over the duration of this research. More than 150,000 flight hours have already been accumulated for over 120 S-92 aircraft. The HUMS data have been used by SAC to support the FAA program. Thus, by selecting the S-92 as the focal aircraft, there were sufficient data to ensure successful achievement of the research objectives. In addition, both the S-76 and UH-60 R&O and R&M databases were used to help guide component selection from a generic perspective.

3.2 COMPONENT AND CBM CREDIT SELECTION.

A representative component was needed to fully explore the issues associated with defining and validating a CBM credit based on HUMS mechanical diagnostics. The scope needed to be consistent with this research objective to address the end-to-end process, including the collection of sample-supporting evidence. It was also optimal to define a credit that was not overly complex, and was sufficiently beneficial for an operator to work with an OEM toward actually implementing the credit validation plan and achieve the credit.

3.2.1 Selection Criteria.

Based on the research objective, the following criteria were defined as the basis for component and credit selection: component history, CBM benefit, CBM credit complexity, CBM credit criticality, inspectability, detectability, availability of seeded fault test data, testability, and synergy with other programs. Each criterion is briefly described below, including the definition of a ranking system and the weighting to be used in the semiquantitative ranking matrix that is used to guide the selection. It must be emphasized that these rankings and weightings are subjective and somewhat dependent on aircraft design and fleet experience. Different OEMs, operators, and stakeholders could establish different rankings and weightings that would result in the selection of a different component or credit. This was not considered important as long as the component and credit were representative and allowed the CBM credit validation process to be fully explored.

3.2.1.1 Component History.

This criterion addresses the selection of a component and credit that would benefit commercial operators. Ranking values of 1 to 5 are used for low to high impact on repair cost or availability. The following are considerations that influence the ranking for candidate components. A component is ranked high (5) if it has low mean time between replacement (MTBR) or TBO, has significant impact on availability, is a primary driver of unscheduled maintenance, or results in high cost of repair if left on the wing too long. For example, TDS hangar bearings are the only drive train components that appear in the top 20 causes for unscheduled aircraft component removals in all three aircraft databases. The TDS hangar bearings and OCBs also have the lowest replacement interval, although the component cost is low. The weighting for this criterion was defined as 3 on a scale of 1 to 5.

3.2.1.2 The CBM Credit Benefit.

This criterion also addresses the selection of a component and credit that would benefit commercial operators, but considers the benefit of early fault detection, of TBO extension, or of reduced inspection regardless of the prevalence of a fault. Ranking values of 1 to 5 are used for low to high benefit, respectively. There would be moderate benefit from the reduction of inspections for all the primary drive train components with exception of the hangar bearings, which would provide only low benefit. The weighting for this criterion was defined as 5 on a scale of 1 to 5.

3.2.1.3 The CBM Credit Complexity.

This criterion addresses the selection of a component and credit that would be of moderate complexity that could be fully addressed within the scope of this FAA research and would require only a limited number of faults to be addressed in the credit validation process. Ranking values of 1 to 5 are used for high to moderate complexity, respectively. The complexity of a full set of credits for the MGB would be very high and very low for hangar bearings. The weighting for this criterion was defined as 4 on a scale of 1 to 5.

3.2.1.4 The CBM Credit Criticality.

This criterion addresses the selection of a component and credit that would be of low to moderate criticality that could be implemented with reasonable direct or indirect evidence. Ranking values of 1 to 5 are used for high to low criticality, respectively. The criticality for the hangar bearings and all gearboxes, with the exception of the input module and accessory gearbox due to redundancy, is high. It is moderate for the oil cooler. The weighting for this criterion was defined as 5 on a scale of 1 to 5.

3.2.1.5 Component Fault Inspectability.

This criterion addresses the selection of a component and credit that would not be readily inspectable by an at-aircraft walk around, but rather, would require at least some level of at-aircraft teardown or removal for teardown and inspection at a depot. Ranking values of 1 to 5

are used for high to low inspectability, respectively. Inspectability for all but the hangar bearings was determined to be low. The weighting for this criterion was defined as 5 on a scale of 1 to 5.

3.2.1.6 Component Fault Detectability.

This criterion addresses the selection of a component and specific faults that are detectable using existing HUMS sensors, or with the addition of minimal additional sensor(s). Ranking values of 1 to 5 are used for low to high detectability, respectively. Detectability was determined to be low for certain faults within the complex planetary gearbox and high for drive shaft hangar bearing faults. The weighting for this criterion was defined as 5 on a scale of 1 to 5.

3.2.1.7 Availability of Seeded Fault Test Data.

This criterion addresses the selection of a component and credit with direct evidence that is already available from other test programs. Ranking values of 1 to 5 are used for low to high availability, respectively. Significant seeded fault test data is available or will likely to be available soon for the oil cooler. Limited data are also available for the IGB and TGB. The weighting for this criterion was defined as 3 on a scale of 1 to 5.

3.2.1.8 Component Fault Testabilty.

This criterion addresses the selection of a component and fault that can be readily tested, or for which direct or indirect evidence can be readily acquired. Ranking values of 1 to 5 are used for low to high testability, respectively. The hangar bearings and oil cooler are the most readily testable. The weighting for this criterion was defined as 3 on a scale of 1 to 5.

3.2.1.9 Synergy With Other Programs.

This criterion addresses the benefit of selecting a component and credit that is synergistic with other programs (e.g., the U.S. Army CBM initiative). Such synergy can result in the availability of test data without the need for additional dedicated tests. Both the oil cooler and hangar bearing were considered under the U.S. Army CBM initiative, with seeded fault data being acquired for CBM validation. Ranking values of 1 to 5 are used for low to high synergy, respectively. The weighting for this criterion was defined as 3 on a scale of 1 to 5.

3.2.2 Component Selection Matrix.

Table 2 summarizes the rankings and weightings used to help guide component selection. The rows of the component selection matrix indicate the criteria defined in section 3.2.1. The number of structural or mechanical failure modes and the number of these failure modes that are Class I (Catastrophic) and Class II (Hazardous) are also shown. These metrics give insight into the potential complexity and criticality of a CBM credit for these components. The columns indicate the weight applied to each criterion and the rank assigned for each of the seven components considered: the MGB, input module, AGB, oil cooler, IGB, TGB, and TDS hangar bearings. All rankings are on a scale of 1 to 5, as defined above. The highest weighting factors were assigned to CBM benefit, CBM credit complexity and criticality, and inspectability and detectability. The remaining criteria were given moderate values. No low-weighted criteria

were included. The total score for each component is obtained by the sum-product of the weighting column and the component ranking column. Based on these scores and careful consideration of the selection criteria and program objectives, the oil cooler was selected as the representative drive train component.

Table 2. Drive Train Component Selection Matrix

Report Section No.	Selection Criteria	Definition of Ranking	Weight	MGB	Input Module	AGB	Oil Cooler	IGB	TGB	TDS Bearing
3.2.1.1	Component history	Low (1) to high (5) impact on cost of availability	3	1	1	1	2	1	1	3
3.2.1.2	CBM benefit	Low (1) to high (5) benefit	5	3	3	3	3	3	3	1
3.2.1.3	CBM credit complexity	High (1) to moderate (5) complexity	4	1	2	3	4	3	2	N/A
3.2.1.4	CBM credit criticality	High (1) to low (5) criticality	5	1	4	5	3	1	1	1
3.2.1.5	Inspectability	High (1) to low (5) inspectability	5	5	5	5	5	5	5	1
3.2.1.6	Detectability	Low (1) to high (5) detectability	5	1	3	3	4	3	3	5
3.2.1.7	Availability of seeded fault test data	Low (1) to high (5) data availability	3	1	3	2	5	3	3	4
3.2.1.8	Testability	Low (1) to high (5) testability	3	1	2	2	5	3	3	5
3.2.1.9	Synergy with other programs	Low (1) to high (5) synergy	3	1	1	1	5	1	1	3
	Total score with weighting			66	104	110	142	96	92	85
	Total score with weighting (without #7-9)			57	86	95	97	75	71	49
	Number of FMEA structural and mechanical failure modes			173	87	39	17	47	59	5
	Number of Class I failure modes			29	0	0	4	18	20	2
	Number of Class II failure modes			14	29	3	0	1	0	0

At the beginning of this research, it was thought that the IGB or TGB were the most desirable selections since they were of moderate complexity and benefit. However, the oil cooler was determined to be the best, even without the last three subjective criteria of testability, availability of seeded fault data, and synergy with other programs. Further, the CBM benefit, despite being ranked the same as the IGB and TGB, is intriguing because it is probable that the 2500-hour MTBR can be extended based entirely on vibration monitoring. When the last three criteria are included, the oil cooler clearly scored much higher than any other component. The availability of test data and synergy with other programs were deemed important due to the ability to focus more on the FAA CBM credit validation process and somewhat less on acquiring seeded fault data. Finally, the selection matrix confirmed the initial opinion that the MGB was too complex for an initial study of CBM credits, and the TDS hangar bearings were too simplistic, but too high a criticality.

Extension of the 2500-hour TBO of the oil cooler was selected as the primary credit that would be considered during the remainder of the research. (Note, this TBO was independently extended, via traditional methods, to 3500 hours during the research, as detailed in sections 7.2 and 7.3.2.) This translates to an extension of the 2500-hour replacement time of the OCBs. The ultimate desire is to go on-condition by eliminating the oil cooler TBO and OCB retirement time through the use of HUMS oil cooler health monitoring.

Additional credit options of modifying or eliminating the 50- and 250-hour inspections were also explored; however, since the 50- and 250-hour inspections relate to faults associated with other oil cooler functions (e.g., oil cooler plumbing, oil cooler by-pass system, and oil pressure sensor manifold), which are not readily monitored through vibration, and are classified as Class II (Hazardous) or Class I (Catastrophic) they are unsuitable for a CBM credit.

3.2.3 Oil Cooler System Description.

The main transmission lubrication system uses an externally mounted oil cooler system, which employs a simple oil-to-air radiator, to maintain safe operating temperatures for the transmission oil. Blowing air across the core of the radiator, using a mechanically driven blower, enhances oil cooling. The blower assembly is driven by the TDS system and provides sufficient cooling of the radiator to lower normal MGB oil temperatures. Major components of the system consist of radiator, blower, and duct assemblies. The blower assembly is monitored for vibration by an accelerometer that interfaces with the aircraft Bearing Monitoring System (BMS).

A cross section of the oil cooler showing the current HUMS/BMS accelerometer location is shown in figure 2. The accelerometer is located inside the blower, mounted between the two bearings, directly in the load path of vibration energy associated with OCB faults. The BMS sensor also provides bearing temperature that detects late-stage bearing failure effects.

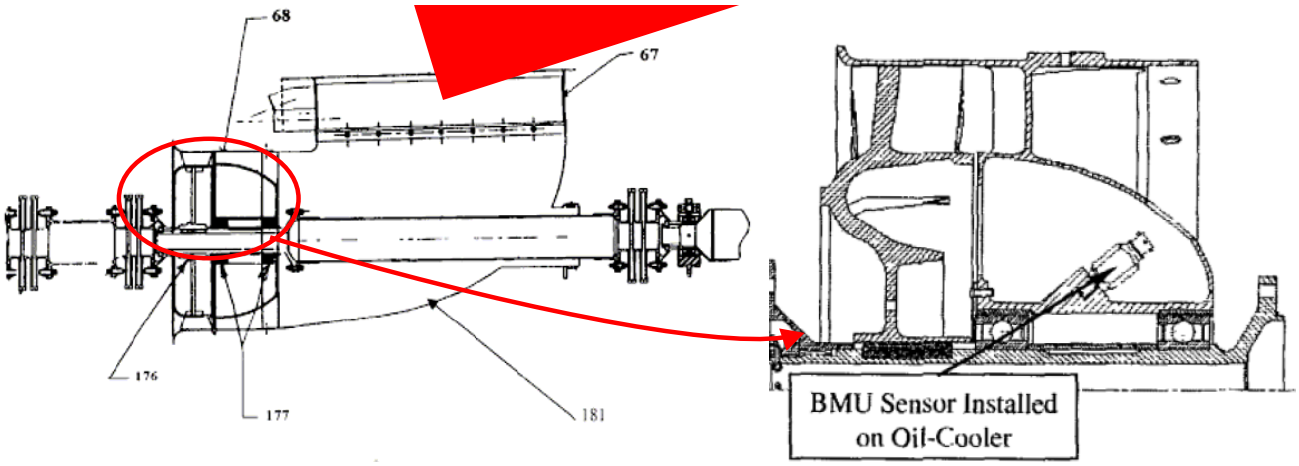


Figure 2. Cross Section of the Oil Cooler Assembly and HUMS/BMS Accelerometer Location

4. APPLICATION OF MG-15 TO THE EXAMPLE CBM CREDIT.

4.1 INTRODUCTION.

The purpose of MG-15 is:

> "To provide guidance to achieve airworthiness approval for rotorcraft HUMS installation, credit validation, and Instructions for Continued Airworthiness (ICA) for the full range of HUMS applications." [1]

MG-15 states that:

> "The certification of HUMS must address the complete process, from the source of data to the intervention action. There are three basic aspects for certification of HUMS applications: installation, credit validation, and Instructions for Continued Airworthiness (ICA)." [1]

This research focused on the application of MG-15 to certify a HUMS mechanical diagnostics application providing a rotorcraft CBM credit. It does not address the certification of a complete HUMS.

4.2 THE MG-15 DEFINITIONS.

MG-15 includes the following definitions:

"1. END-TO-END: The term "end-to-end" is intended to address the boundaries of the HUMS application and the effect on the rotorcraft. As the term implies, the boundaries are the starting point that corresponds with the airborne data acquisition to the result that is meaningful in relation to the defined credit without further significant processing. In the case where credit is sought, the result must arise from the controlled HUMS process containing the three basic requirements for certification as follows:

(i) Equipment installation/qualification (both airborne and ground),
(ii) Credit validation activities, and
(iii) Instructions for Continued Airworthiness activities.

2. Credit: To give approval to a HUMS application that adds to, replaces, or intervenes in industry accepted maintenance practices or flight operations.

3. Application(s): A HUMS process implemented for a distinct purpose(s).

4. Criticality (1309): This term describes the severity of the end result of a HUMS application failure/malfunction. Criticality is determined by an assessment that considers the safety effect that the HUMS application can have on the aircraft. There are five criticality categories as follows:

(i) Catastrophic: Failure conditions, which would prevent continued safe flight and landing.

(ii) Hazardous/Severe Major: Failure conditions, which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

(A) A large reduction in safety margins or functional capabilities,

(B) Physical distress or higher workload such that the flight crew could not be relied on to perform their tasks accurately or completely, or

(C) Adverse effects on occupants including serious or potentially fatal injuries to a small number of those occupants.

(iii) Major: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.

(iv) Minor: Failure conditions which would not significantly reduce aircraft safety, and which would involve crew actions that are well within their capabilities. Minor failure conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload such as routine flight plan changes, or some inconvenience to occupants.

(v) No-Effect (Non-hazardous class): Failure conditions which do not affect the operational capability or safety of the aircraft, or the crew workload.

5. Integrity: Attribute of a system or a component that can be relied upon to function as required by the criticality determined by a Failure Hazard Assessment (FHA).

6. Mitigating Action: An autonomous and continuing compensating factor which may modify the level of qualification associated with certification of a HUMS application. This action becomes a part of the certification requirements and, as such, is required to be performed as long as that certification requirement is not changed by a subsequent re-certification. An example of a mitigating action is a pilot's comparison of airborne HUMS data with aircraft instrument data.

7. Synthesis: The process of evaluating service history and any other relevant data with the objective of validating and, if necessary, refining the performance of an approved credit." [1]

4.3 CERTIFICATION PROCESS FOR A HUMS APPLICATION PROVIDING A CBM CREDIT.

The three aspects of HUMS certification (installation, credit validation, and ICA) are not totally independent and have varying interactions with each other. MG-15 states that:

> "Installation includes all the equipment needed for the end-to-end application that is associated with acquiring, storing, processing, and displaying the HUMS application data, including airborne and ground-based equipment. Credit validation includes evidence of effectiveness for the developed algorithms, acceptance limits, trend setting data, tests, etc., and the demonstration methods employed. A plan is needed to ensure continued airworthiness of those parts that could change with time or usage and includes the methods used to ensure continued airworthiness." [1]

Although noting relevant installation and ICA aspects, this research on the approval of a CBM credit is primarily targeted at the aspect of credit validation.

The certification process begins with the declared application intent which, in this case, is for credit. An FHA is performed to determine the end-to-end criticality for the application. HUMS integrity criteria can then be established—the integrity level is required to be equivalent to the determined end-to-end criticality. Demonstrating compliance with the established criticality level may be achieved by a combination of application qualification plus appropriate mitigating actions.

MG-15 includes the following note:

> "A certification plan may be provided to assist in the certification process. At a minimum, this plan should address the proposed means of compliance to each applicable paragraph of this advisory circular for a given application." [1]

4.4 INSTALLATION.

MG-15 states that:

> "Installation approval must cover systems and equipment that acquire, store, process, and display HUMS data and includes the airframe installation, or any one of these functions for a particular application. HUMS equipment requirements consist of common requirements plus the unique requirements of airborne and ground-based equipment." [1]

This research only considers installation aspects that are relevant to the HUMS mechanical diagnostics application for the selected CBM credit. Therefore, only the common HUMS

equipment requirements are addressed—where a common requirement is one that applies to airborne, ground-based, and installation equipment. These common requirements are discussed in sections 4.4.1 through 4.4.3.

4.4.1 Criticality Determination.

Criticality is determined from the FHA and is a primary decision point relating to the depth of requirements for certification. A HUMS application providing a credit will have a criticality level in the category of Minor, Major, or Hazardous/Severe-Major (MG-15 currently does not address the Catastrophic criticality category).

MG-15 states that:

> "The FHA is a top down analysis (which should involve pilots and flight analysts as well as engineers) that starts with the hazards to the rotorcraft and traces these hazards to the system, subsystem, and component level in the areas affected by HUMS. This type of analysis starts with the determination of what undesirable effects can occur as a direct or indirect result of using HUMS for maintenance or operational actions. The level of severity associated with this effect will result in assigning a criticality level." [1]

The final level of equipment qualification may not only be the result of technical considerations, but also the result of other mitigating actions, which can result in a reduction of qualification levels for equipment.

4.4.2 Mitigating Actions.

MG-15 states that:

> "A mitigating action is an autonomous and continuing compensating factor which may modify the level of qualification associated with certification of a HUMS application. These actions are often performed as part of continued airworthiness considerations and are also an integral part of the certification. As such, the continuation of certification limitations, where appropriate, must be included in the ICA. Mitigating actions are subjective in nature and are an intended method(s) of application where the pre-mitigated levels of integrity are defined." [1]

4.4.3 Performance.

MG-15 states that:

> "There must be minimum end-to-end performance criteria consistent with the application's intended use. Performance criteria, as a minimum, should consider accuracy, timing/sampling, resolution, event recognition, and consistency. The HUMS signal source must be compatible with the determined qualification level. Tests should be conducted to demonstrate that these criteria are met." [1]

4.5 CREDIT VALIDATION.

This part of MG-15 is the primary focus area of the research work:

> "HUMS applications for which credits are sought must be validated. For each application, evidence shall be provided that the physics involved is understood and therefore that the monitoring technique/algorithm/parameter, rejection criteria, and associated intervention actions are well chosen. The designer of the component/equipment to be monitored is the most logical choice for this determination. However, in some cases the source can be from any organization as long as the validation criteria herein can be satisfied. If changes are proposed to an approved system, re-evaluation is required to ensure existing credit(s) are not invalidated. The degree of effort will vary and depend on the application type, the credit sought, and the consequences of failure or any other malfunction. The validation process would generally need to include the following:
>
> - Description of application and associated credit.
> - Understanding of the physics involved.
> - Validation methodology.
> - Introduction to service.
> - Continued airworthiness (synthesis)." [1]

As the manufacturer of the S-92 helicopter on which the HUMS CBM credit is being sought, SAC could define the HUMS monitoring requirements, rejection criteria, and appropriate intervention actions. As a leading HUMS supplier, GE Aviation could act as an advisor on the HUMS monitoring requirements.

4.5.1 Description of Application and Associated Credit.

The starting point for the HUMS approval process is described in sections 4.1–4.4. An FHA is then performed to determine the associated level of criticality. MG-15 states that:

> "It is important to fully evaluate and describe the proposed credit and the worst effect on the rotorcraft should the application fail or malfunction. This evaluation is needed to determine the system criticality, the system installation integrity requirements, and the depth and scope of the credit validation effort." [1]

MG-15 provides clear statements of the requirements for credit validation, which are repeated in sections 4.5.2 through 4.5.5.

4.5.2 Understanding the Physics Involved.

MG-15 states the Physics of Failure as:

> "The mechanisms of failure and/or degradations associated with the requested credit should be understood. This includes how a failure occurs and/or at what rate the degradation progresses and a determination of the point where intervention action is necessary. For some complex applications, this may include supporting information from validated analytical tools such as finite element analysis and fracture mechanics.
>
> These understandings should be used to determine the four important characteristics of a HUMS application:
>
> (A) The technique to be used.
>
> (B) The appropriate alert limits, including trending where appropriate.
>
> (C) The appropriate intervention action.
>
> (D) How often to monitor to give optimum opportunity for the intervention action to be effective.
>
> This should also recognize the different characteristics of the failure/degradation and determine when trending or a step function is most appropriate." [1]

4.5.3 Validation Methodology.

With respect to the validation methodology, MG-15 states:

> "All HUMS applications should have their validation process based on suitably representative physical data. This process may use direct or indirect evidence, or a combination of the two, depending upon the credit type and the criticality on the aircraft of any HUMS failure or malfunction.
>
> (i) Direct Evidence.
>
> When the HUMS application is classified as Hazardous/Severe Major, then direct evidence must be gathered. Examples of where this might be the most appropriate method include maintenance tasks such as vibration checks for imbalance/misalignment of high energy rotating equipment, fatigue life counting, or going "on-condition" for flight critical assemblies.

Direct evidence is required for establishing that the HUMS application is sensitive to and obeys predicted response rules for the damage type, giving consistent alerts. This evidence may be gathered from several sources as follows:

(1) Actual service experience on HUMS equipped aircraft,

(2) "Seeded tests" (where the wear, defect, or deterioration is introduced, allowed to develop, and the technique response verified), and

(3) On-aircraft trials, investigating cause and effect (for example, introducing degrees of imbalance and calibrating the techniques response).

Tests should be representative of the aircraft for which the credit is being sought and of test conditions representing the flight regime that would prevail when data is normally gathered (e.g., cruise). It should be established that the evidence gathered from on-aircraft ground trials or rig based seeded tests is valid in flight.

(ii) Indirect Evidence.

When the HUMS application is classified as "Major" or lower, indirect evidence may be gathered. Criteria for this approach include a criticality determination of Major or lower and either or both; application to "on-condition" maintenance actions, and/or lowering the probability of undetected failures. Monitoring of a high number of potential failure modes can collectively determine the probability of undetected failures. Here, it may not be practicable to generate direct evidence for each failure.

Proven analytical methods may be combined with sound engineering judgment to provide calculated/derived criteria; tests can be performed to validate these criteria. Model based analytical methods for predicting damage progression (e.g., finite element analysis and fracture mechanics) may allow for a validation by claiming analogy with 'direct' evidence generated for other aircraft types or equipment. However, to more fully validate this analogous data set, a degree of direct evidence for the actual equipment being monitored is still likely to be necessary to prove similarity of application. This might be achieved by performing an appropriate number of seeded defect tests and, in effect, "sampling" the range of failure types contained.

NOTE: For both direct and indirect evidence, the whole system must be validated end-to-end." [1]

4.5.4 Controlled Introduction to Service.

With respect to controlled introduction to service, MG-15 states:

"For some credit applications, full validation and implementation may be possible during the development period. However, for many HUMS techniques, a plan for a controlled introduction to service may be necessary to fully validate the credit.

There must be provisions in the certification process to instruct the continued airworthiness effort to ensure compliance with the aforementioned plan.

During the implementation of this plan, data is accumulated by operational aircraft, and from this data, refinements and adjustments to the original criteria can be made. This period may also allow a proposed credit to be operated in parallel with alternative or standard procedures when it is necessary to gain additional in-service validation by way of back-to-back comparison.

The plan should include procedures and provisions for this controlled period and should include clear goals by which progress and ultimately termination of this phase can be measured. The plan may include a multi-credit HUMS that will require a phased introduction of credits." [1]

4.5.5 Continued Airworthiness and Synthesis of Credit.

In terms of Continued airworthiness and Synthesis of credit, MG-15 states:

"Normal and established procedures will prevail for HUMS as for all other continued airworthiness matters. Arrangements should be made to validate the performance of an approved credit throughout its service use. Provisions should be made to allow for the synthesis of the service experience with relevant engineering evidence from rejected components, development testing, seeded testing, etc. Any necessary or desired modifications to the HUMS application or the component/equipment being monitored must be re-evaluated." [1]

4.6 INSTRUCTIONS FOR CONTINUED AIRWORTHINESS.

This is the final part of MG-15 that is relevant to this research. Again, the MG-15 requirements are clear and are repeated below.

"The applicant for HUMS is required to provide ICA developed in accordance with FAR/JAR Part 29 and Appendix A. This section provides supplemental guidance with addressing aspects unique to HUMS. The ICA should address HUMS integration with the aircraft. This section addresses both airborne and ground-based systems and equipment.

(i) HUMS ICA Items

The applicant must address the following subjects in addition to FAR/JAR Part 29. These subjects should address both airborne and ground-based systems and equipment unless specifically indicated otherwise.

(A) Control and operating instructions must be provided for each element of HUMS, and where applicable, include data acquisition, transfer processing, display, configuration management, and resulting actions.

(B) Acceptance and rejection criteria and associated actions must be defined.

(C) A procedure is required when the system becomes inoperative because data is missing.

(D) When required, there must be a procedure for collecting and transferring HUMS data when the aircraft is away from the main HUMS data processing base.

(E) Provide a procedure for independent verification, if applicable.

(F) Provide a procedure for implementing mitigating actions, when mitigating actions are applied.

(G) Provide a procedure for implementing controlled introduction to service instructions, if applicable.

(H) Provide a training program on HUMS airborne and ground-based systems and equipment.

(I) The airworthiness limitation section must be amended to address the following, if required:

(1) Requirements for independent verification and associated procedures.

(2) Requirements for mitigation actions and associated procedures.

(3) Requirements for controlled introduction to service and associated procedures.

(ii) Ground-Based System and Equipment

A procedure must be defined to ensure the security of the ground-based system and equipment and the integrity of the HUMS data." [1]

4.7 RESULTS FROM MG-15 REVIEW.

The review of MG-15 initially concluded that the document provides useful guidance material, is generally structured in a logical manner, and contains well-founded requirements. Although these are defined in generic terms, they are considered to be appropriate for a document of this type. When applying MG-15 to the end-to-end process of achieving a particular CBM credit potential issues to be addressed may include

- understanding the interactions between requirements in different sections of the document, primarily between the sections on installation and credit validation.

- converting the generic guidance into specific plans for a defined HUMS application providing a CBM credit that is deemed acceptable to a certifying authority (this is a key focus of the research).

- determining the cost effectiveness and appropriate timing of any CBM credit application. For example, conducting a series of seeded fault tests to provide direct evidence to validate a credit can be expensive. However, after a number of years of HUMS operations on a reasonably sized helicopter fleet, much of the required direct evidence may have been accumulated from the in-service experience at little cost. This indicates the importance of having an effective HUMS maturity plan that ensures that data and evidence from in-service experience is properly documented and reviewed.

5. DEFINITION OF THE TARGET CBM CREDIT CRITICALITY AND VALIDATION REQUIREMENTS.

5.1 CREDIT CRITICALITY.

The credit criticality was based on a solid understanding of the physics of failure, which are documented in an FMEA, in an internal SAC report [2]. A high-level summary of this assessment is included here.

Extension or elimination of the oil cooler TBO and bearing replacement times could increase the possibility of OCB faults. The FMEA, however, remains unchanged since the FMEA analyzes all possible failure modes without regard to probability of failure. The primary failure mode that drives the criticality for this target credit is OCB failure, which can result from the other bearing failure modes (i.e., wear, sliding, pitting/spalling/cracking, and cage fracture). The following are generic summaries of two bearing fault progressions that must be considered. Either bearing fault progression may result from a number of initial causes, such as loss of grease, contamination, or shaft misalignment.

1. Bearing wear, sliding, pitting, spalling, and/or cracking → increased vibration → increased wear rate → excessive vibration

2. Bearing cage failure → bearing failure → possible loss of shaft position or bearing seizure → excessive vibration → possible impeller/stator impact → possible impeller failure → loss of oil cooling

The first progression is classified as a Class IV (Minor) effect because the primary end effect is excessive oil cooler vibration, which would not reduce the functionality of the aircraft or increase pilot workload. The second progression is classified as Class III (Major) effect, defined in MG-15 as:

> "Major: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions

impairing crew efficiency, or discomfort to occupants, possibly including injuries." [1]

The classification is Major, as opposed to Hazardous/Severe Major, because compensating provisions (i.e., multiple redundant fasteners (MRF), periodic inspection, and HUMS/BMS monitoring) result in end effects (e.g., noise, vibration, and OCB temperature, and oil temperature increases), which are detectable before conditions become hazardous. It is important to note that the OCB design and TBO criticality is based on multiple compensating provisions, of which HUMS/BMS monitoring plays a support role. The use of an MRF design approach reduces the likelihood and inherent criticality of the end effects associated with bearing failure. Periodic inspection and HUMS/BMS monitoring provide the means to detect faults in early rather than late stages of failure progression. The HUMS/BMS vibration monitoring of the OCBs maximizes the likelihood that a bearing failure will be detected before it results in complete bearing failure. Even if the HUMS/BMS fails to detect the vibration, increased bearing temperature and ultimately oil temperatures due to loss of oil cooling are indicated in the cockpit.

5.2 FAULT DETECTION REQUIREMENTS.

The primary faults that must be detected to completely eliminate the bearing replacement and oil cooler TBO are the two failure modes listed in the FMEA, which are classified as Class III (Major); bearing failure and cage failure. The detection of a bearing failure must occur before bearing damage and collateral fan damage can become hazardous. In fact, to provide overall benefit to the operator, fault detection must occur prior to expensive collateral damage and in sufficient time to allow the maintainer to proactively schedule maintenance, as opposed to reactively pulling an aircraft from service. Thus it is desired that HUMS reliably detects the other failure modes (e.g., spall, sliding, and wear), which are leading indicators and result only in excessive oil cooler vibrations (Class IV (Minor)).

5.3 THE CBM CREDIT VALIDATION PLAN.

A CBM credit validation plan (see appendix A) was produced for the example S-92 OCB CBM credit. The plan complies with the guidance contained in MG-15 and follows the list of topics defined within it.

- Description of application and associated credit
- Understanding of the physics involved
- Validation methodology
- Introduction to service
- Continued airworthiness (synthesis)

Although addressing a particular example CBM credit, the intention of this report is to provide a general framework for credit validation of HUMS mechanical diagnostics applications. This report also contains some technical justification for the defined approach to credit validation. In particular, it includes a detailed consideration of the use of indirect evidence for credit validation. It would be difficult to validate many HUMS CBM credits on the basis of direct evidence alone as the associated component testing would be prohibitively expensive, or it would be necessary

to wait a very long time for direct in-service experience to accumulate. In many cases, generic relationships can be defined between component faults and the features generated by these faults in monitored signals, such as vibration, providing a clear technical justification for using indirect evidence. However, clear criteria are defined for assessing the relevance of any such evidence (see appendix A.4.1).

6. ACQUISITION AND ANALYSIS OF OIL COOLER DATA FOR CREDIT VALIDATION.

6.1 REVIEW OF RELEVANT SAC OCB EXPERIENCE.

SAC's S-92 and UH-60 OCB experience was reviewed relative to the S-92 bearing failure modes. The S-92 failure modes consist of five categories: seal problems, phenolic cage faults, raceway faults, ball faults, and grease issues. Each category was further broken down into failure modes. The following sections describe each category and SAC's field experience. The information is also summarized in table 3 for quick reference. The table includes the probability of occurrence, a timeline for the failure mode occurrence relative to other failure modes, indication if the failure mode is caused by a manufacturing issue or a fatigue/debris issue, the most likely candidate for detection of the failure mode, and whether the failure mode has been observed in the S-92 or UH-60 fleet.

Table 3. The SAC S-92 OCB

Failure Category	Failure Mode	Probability (L, M, H)	Criticality	Timeline	Manufacturing Issue	Fatigue/ Debris Issue	Detection		S-92 Fleet	UH-60 Fleet
							Vibes	Temperature		
Seal problem	Indented	L	Minor	1	X		X		X	N/A, shielded
	Cracks, wear	L	Minor	1		X				N/A, shielded
Phenolic cage fault	Cracks	L	Minor	2		X				N/A, steel
	Breaks	L	Major	3		X	X	X		N/A, steel
Raceway fault	Light to medium spalls	M	Minor	2		X	X		X	
	Light to medium corrosion/pits	M	Minor	2		X	X		X	X
	Severe corrosion/pits	L	Minor	3		X	X			X
Balls fault	Dents	L	Minor	1	X		X		X	
	Light to medium spalls	L	Minor	2		X	X			
	Light to medium corrosion/pits	M	Minor	2		X	X		X	X
	Sever corrosion/pits	L	Minor	3		X	X			
Grease issue	Contaminated/ degraded	M	Minor	1		X				X
	Loss of lubrication/ oxidized	L	Major	3		X	X	X		

L = Low
M = Medium
H = High

6.1.1 Seal Problems.

Seal problems can be the result of a manufacturing issue or the result of fatigue. On the S-92, improper seating of the seals, due to manufacturing issues, was observed. The result was seal degradation, which leads to increased vibration. If left undetected, the mode could potentially increase the rate of bearing deterioration. Another potential seal problem is the development of cracks or improper sealing due to fatigue. The initial failure type can only be discovered by visual teardown inspection, but the next step in the timeline would be the introduction of foreign object damage (FOD) or moisture into the bearing. If the FOD or moisture becomes detrimental to the bearing, it could lead to corrosion or degradation of lubrication, causing raceway or ball pitting and wear, and ultimately, bearing failure after a prolonged period. Either raceway or ball pitting are detectable failure modes. The probability of either manufacturing issues or fatigue failure occurring to the seals is low with criticality levels of minor. Fatigue issues with seals have not been observed within the S-92 fleet. Neither type is applicable to similar bearings that have shielded, rather than sealed, designs. However, shielded designs are more susceptible to both FOD and moisture penetration, which can lead to corrosion, raceway pitting, and ball pitting.

6.1.2 Phenolic Cage Faults.

The S-92 OCB phenolic cage can develop the following two types of failures: cracks or breaks. Both types have a low probability of occurrence. The cracks and breaks have negligible effects and, therefore, would be undetectable; they have a criticality level of Minor. Breaks could potentially lead to loss of ball placement from cage displacement and loss of axial position in the shaft. The phenolic cage is seize-resistant, but the loss of axial position in the shaft could lead to fan clearance issues. The loss of ball placement is classified with a Major criticality level. For a phenolic cage break to occur and lead to loss of ball placement, several other failure types would most likely preexist and result in a detectable warning. Severe spalling or pitting of the raceways or balls would need to exist for enough energy to be present to break and displace a phenolic cage. Phenolic cage faults have not been observed in the S-92 fleet. Cage faults leading to loss of ball placement are more applicable to bearings having a stamped steel cage.

6.1.3 Raceway Faults.

Raceway faults consist of the following three failure mode types: light to medium spalls, light to medium corrosion/pits, or severe corrosion/pits. All three failure mode types have a Minor criticality level. Raceway faults are attributed to corrosion, degradation of lubrication, or contaminated lubrication. Severe spalls are not included in the failure mode description due to the low surface contact stresses in the OCB, which has relatively light loading. It is believed a spall, if introduced, would not have sufficient load to grow. However, light to medium spalls could be introduced due to contaminated lubrication. An example of this type of spall was discovered in the S-92 fleet; therefore, light to medium spalls are considered to have a medium probability of occurring. Light to medium corrosion/pits were observed in both the S-92 and UH-60 fleet. The likelihood for corrosion/pits increases with time; therefore, light to medium corrosion/pits would have a probability of high if the TBO were eliminated. Based only on the current TBO, the probability is medium. The shielded design has a higher likelihood of the corrosion occurring earlier in life, but both have a risk due to the material used and the environment in which the bearings operate. With the current TBO, severe corrosion/pits would have a low likelihood of occurring. As the TBO is increased, monitoring should keep the occurrences low.

6.1.4 Ball Faults.

Ball faults consist of four failure model types: dents, light to medium spalls, light to medium corrosion/pits, or severe corrosion/pits. All four failure mode types have a Minor criticality level. Ball faults are attributed to corrosion, degradation of lubrication, or contaminated lubrication. Severe spalls are not included in the failure mode description due to the low surface contact stresses resulting from relatively light loading, and it is assumed that a spall if introduced would not have a sufficient load to grow. However, light to medium spalls could occur due to contaminated lubrication. Light to medium spalls on the balls have not been discovered in the S-92 and UH-60 fleet to date.

In a review of the S-92 assembly process, it was discovered that an avenue existed for the possibility of dents to be created during assembly. The deficient process has been corrected, but

the end result is still considered. If undetected, the ball dents could accelerate the bearing degradation timeline.

Light to medium corrosion/pits were discovered in both the S-92 and UH-60 fleets. As the time the bearing is allowed to stay in use increases, the likelihood for corrosion/pits increases; therefore, light to medium corrosion/pits would have a high probability. Based only on the current TBO, the probability is medium. The shielded design has a higher likelihood of corrosion occurring earlier in life, but both have a risk due to the material used and the environment in which the bearings operate. With the current TBO, severe corrosion/pits would have a low likelihood of occurring. As the TBO is increased, monitoring should still keep the occurrence as a low likelihood.

6.1.5 Grease Issue.

Grease issues consist of two failure types: contaminated/degraded or oxidized. The contaminated grease is driven by the location of the bearings. The shielded design is more susceptible to this type of failure. The sealed bearing reduces the probability of this occurring, but the failure mode should still be considered. The failure mode is more of a precursor to raceway and ball faults. It is categorized as a probability of low and a criticality level of Minor.

Complete loss of lubrication is the worst-case grease issue. This state can be reached if the grease becomes oxidized. Neither the S-92 nor the UH-60 fleet experienced this failure mode. Complete loss of lubrication has a probability of low and a criticality level of Major. The S-92 bearing design has the benefit of a phenolic seize-resistant cage design. However, the complete loss of lubrication increases the likelihood of ball and raceway damage, increased bearing temperatures, and bearing failure. The complete loss of lubrication may be associated with several other failure modes as a precursor.

6.2 IDENTIFICATION OF EXISTING OIL COOLER RIG DATA.

SAC identified existing S-92 and UH-60 oil cooler rig data sets and categorized them with respect to coverage of the bearing failure modes, repeatability, and detectability. A gap analysis was then performed to develop the oil cooler test plan, with the primary objective of gathering direct evidence to support the validation process for the target CBM credit of extending/eliminating the S-92 oil cooler TBO. The plan allowed sufficient data to be gathered to demonstrate and evaluate the validation process. It was not intended to contain all data required to fully certify the maintenance credit.

The gap analysis is summarized in table 4 and identifies the suitable test sets: UH-60 tests (performed by Sentient Corporation, hereafter referred to as Sentient), UH-60 HUMS SAC test, S-92 BMS Qualification tests, S-92 fleet investigation, and the CBM tests conducted for the FAA program. The tests generated data that could be used for analysis to help understand a failure mode, repeatability, or detectability are marked with an X. The following sections discuss the relevance and gaps of existing data sets for each failure mode.

Table 4. The OCB Rig Experience

Failure Mode	Failure Type	Probability (L, M, H)	Criticality	Sentient UH-60 Tests	UH-60 HUMS Test	S-92 BMS Qualification Tests	S-92 Fleet Investigation	FAA CBM Tests
Seal problem	Indented	L	Minor	N/A, shielded	N/A, shielded		X	
	Cracks, wear	L	Minor	N/A, shielded	N/A, shielded			
Phenolic cage fault	Cracks	L	Minor	N/A, steel	N/A, steel			X
	Breaks	L	Major	N/A, steel	N/A, steel			P-create
Raceway fault	Light to medium spalls	M	Minor					X
	Light to medium corrosion/pits	M	Minor	X		X		P-H60
	Severe corrosion/pits	L	Minor	X				P-H60
Balls fault	Dents	L	Minor					P-create
	Light to medium spalls	L	Minor					
	Light to medium corrosion/pits	M	Minor	X		X		P-H60
	Sever corrosion/pits	L	Minor					
Grease issue	Contaminated/ degraded	M	Minor	X	X	X		
	Loss of lubrication/ oxidized	L	Major		X			P-create
Repeatability	Build-to-build			X	X		X	
	Point-to-point							X
	Time effect			X			X	X
	Cooler-to-cooler				X		X	
	Speed variation (100%-108%)					X		
	Misalignment (1.25 degrees)					X		
	Imbalance (30 lb radial)					X	X	X
Detectability	Fwd versus aft				X		X	X
	Sensor location				X			X

L = Low probability
M = Medium probability
H = High probability
The FAA CBM Tests column refers to a plan to either create the required data set by performing rig tests (listed as P-create) or by using UH-60 data for the CBM credit (listed as P-H60).

6.2.1 Seal Problems.

The seal problems were examined in detail during the S-92 fleet investigation. Several bearings were brought back from the fleet and tested in-house on a representative oil cooler rig. Fleet data flagged the issue. Since probability was low, criticality was Minor, and data existed, no additional test data were required.

6.2.2 Phenolic Cage Fault.

No data existed from in-house tests of phenolic cage faults. Since this had Major criticality classification, additional data were required.

6.2.3 Raceway Fault.

Sentient completed an extensive test of UH-60 OCBs with varying amounts of corrosion and pits on the raceway. Unfortunately, data did not include a reference sensor in the S-92 BMS location. During the S-92 BMS qualification, lubrication was degraded to create raceway faults. The tests verified that damage existed, but the final condition of the bearings was not clear. Because this fault had a higher probability of occurrence; additional data were required.

6.2.4 Ball Faults.

Sentient also completed tests of UH-60 OCBs with varying amounts of corrosion and pits on the balls. Unfortunately, the data did not include a reference sensor in the S-92 BMS location. During the S-92 BMS qualification, lubrication was degraded to create ball faults. The tests verified damage existed, but the final condition of the bearings was not clear. Because this fault had a higher probability of occurrence, additional data were required.

6.2.5 Grease Issue.

The UH-60 SAC tests indicated the bearings required minimal grease to operate, based on results from chemically degreased bearings. However, no data existed from in-house or available external tests of phenolic cages without lubrication. Because this was classified as a Major, additional data were required.

6.2.6 Repeatability.

Repeatability of results was necessary to understand and use results from various data sets and, eventually, to establish vibration thresholds. Items that could affect the results were identified. The top seven items considered were the following: build-to-build, point-to-point, time effect, cooler-to-cooler, shaft speed variation, misalignment, and imbalance. Build-to-build entailed using the same bearings and cooler and quantifies the effect of teardown and reassembly. Point-to-point examined running the same bearings and cooler without teardown. Time effect examined the stabilization time of bearings. Cooler-to-cooler entailed using the same bearings in two different coolers. Speed variation entailed the effect of speed on bearing energy. Misalignment investigated the effect of the known acceptable tolerance in the shaft alignment.

Imbalance is understanding the effect of the known acceptable tolerance in shaft balance on the vibration results.

The existing databases covered the majority of these effects. The one item not adequately covered was point-to-point variations, which required additional data. Imbalance and time had noticeable impacts from previous tests. These items were reexamined and required additional data.

6.2.7 Detectability.

To ensure the effects of detectability are understood bearing defect and sensor locations need to be investigated. The bearing defect location determines whether the defective bearing is physically located in the forward or aft bearing location on the blower shaft. The sensor location validates the ability of S-92 BMS sensor to detect faults in both locations. There was limited data from the UH-60 and the S-92 fleet investigations. To be complete, a full suite of instrumentation locations was needed. For example, for known faults, the defective bearing was tested at both the forward and aft locations to gather more data on detectability effects.

6.3 OIL COOLER RIG TEST PLAN.

Phase 1 of the test plan focused on collecting baseline data, LTF data, repeatability effects, and detectability effects, as outlined in table 5. The LTF data included bearings with light spalling and disassembly-induced cracked cages. The repeatability effects included point-to-point, time effect, and imbalance. The detectability effects included defect location and sensor location.

Table 5. Phase 1 Oil Cooler Test Plan

					S-92 OCB**				
		Test Location							
Test	Test Duration (hour)	Oil Cooler Rig	Sentient Rig	Shaft Imbalance*	Healthy	Field Issue (Aircraft 27)	LTF 2500+	Pulled for High Hours 2500+	Objective
1	1	X			FWD/AFT Aircraft 67				Baseline
2	1	X		X	FWD/AFT				
3	1	X				FWD/AFT 8841/8844			Detect and characterize bad vibrations
4	1	X		X		FWD/AFT 8841/8844			
5	1	X					FWD/AFT 5785/5801		Characterize normal vibrations at 2500 hours that were being pulled due to time, not vibration limits.
6	1	X		X			FWD/AFT 5785/5801		
7	1	X						FWD/AFT Aircraft 8	Characterize normal vibrations at 2500 hours that are being pulled due to time, not vibration limits.
8	1	X		X				FWD-AFT Aircraft 8	

Table 5. Phase 1 Oil Cooler Test Plan (Continued)

Test	Test Duration (hour)	Test Location		Shaft Imbalance*	S-92 OCB**				
		Oil Cooler Rig	Sentient Rig		Healthy	Field Issue (Aircraft 27)	LTF 2500+	Pulled for High Hours 2500+	Objective
9	1	X			AFT 5796		FWD 5793 (2 spalls)		Sensitivity to location. Ability to detect a single fault. Transmission path.
10	1	X		X	AFT 5796		FWD 5793 (2 spalls)		
11	1	X			FWD 5796		AFT 5793 (2 spalls)		Sensitivity to location. Ability to detect a single fault. Transmission path.
12	1	X		X	FWD 5796		AFT 5793 (2 spalls)		

*Shaft imbalance created to amplify known vibration issues. Imbalance should be created at current field experience to be representative.
**Maintain original face orientation when swapping bearings.

Phase 2 of the test plan conducted by Sentient focused on tests for failure progression and failure detection, as outlined in table 6. The failure progression tests included cage break and loss of lubrication progressions with medium spalling. The failure detection tests included bearings with corrosion and pitting, assembly dent defects, and two spalling levels.

Table 6. Phase 2 Oil Cooler Test Plan

Test	Description	Objective
1	14-point tests with UH-60 bearings installed in S-92 blower. Need to run good sample of bearings that span across 5 levels of corrosion and pitting. Potential set: Bearings 08, 11, and 13 had no damage; bearings 14, 15, and 20 had trace damage; bearings 02, 10, and 12 had light damage; bearing 19 had moderate damage; and bearings 05, 06, 21, and 17 had severe damage.	• Measure detection horizon for BMU location in S-92 oil cooler. • Quantify correlation to UH-60 location.
2	2(a) Create dent on S-92 ball bearings for one bearing specimen. 2(b) Run point test in S-92 blower. 2(c) Repeat with imbalance.	(1) Simulate S-92 manufacturing/assembly issue with dents on balls. (2) Characterize signature. Signature should be similar for spall. (3) Measure effect of radial load on bearing with defect.
3	Using S-92 bearing with cage fracture create break. Run bearing until torque in bearing rig hits its limit or until 200 hours is reached. Inspect at 100 hours. May modify test if not progressing. Final teardown and inspection.	(1) Characterize cage failure mode. (2) Characterize cage failure progression.

Table 6. Phase 2 Oil Cooler Test Plan (Continued)

Test	Description	Objective
4	4(a) Using bearing with slight spall run point test in S-92 blower. 4(b) Repeat with imbalance. 4(c) In bearing rig, increase loads to grow spall to medium size. 4(d) Run point test in S-92 blower. 4(e) Repeat with imbalance.	(1) Characterize light spall signature. (2) Characterize medium spall signature. (3) Characterize imbalance effect.
5	Degrease bearing from test 4. Run bearing until torque in S-92 blower stand hits its limit or until 200 hours is reached. Inspect at 100 hours. May modify test if not progressing. Final teardown and inspection	(1) Characterize loss of lube failure mode. (2) Characterize loss of lube failure progression.

6.4 GATHERING OF DIRECT AND INDIRECT EVIDENCE FOR CREDIT VALIDATION.

6.4.1 Database of S-92 Oil Cooler HUMS Data and Maintenance Actions.

SAC provided a database of S-92 oil cooler and TDS hangar bearing HUMS BMS data containing over 3 years of data (ending July 27, 2008) from a fleet of 85 S-92 aircraft.

The data were from two BMS sensors located on the oil cooler and the adjacent TDS hangar bearing, as shown in figure 3. The BMS sensors acquire both vibration and temperature data, but the analysis concentrated on the vibration data because this was the primary interest in the research program. To prevent traceability by GE Aviation or other third parties to customer's data, random identifiers were assigned to specific tail numbers.

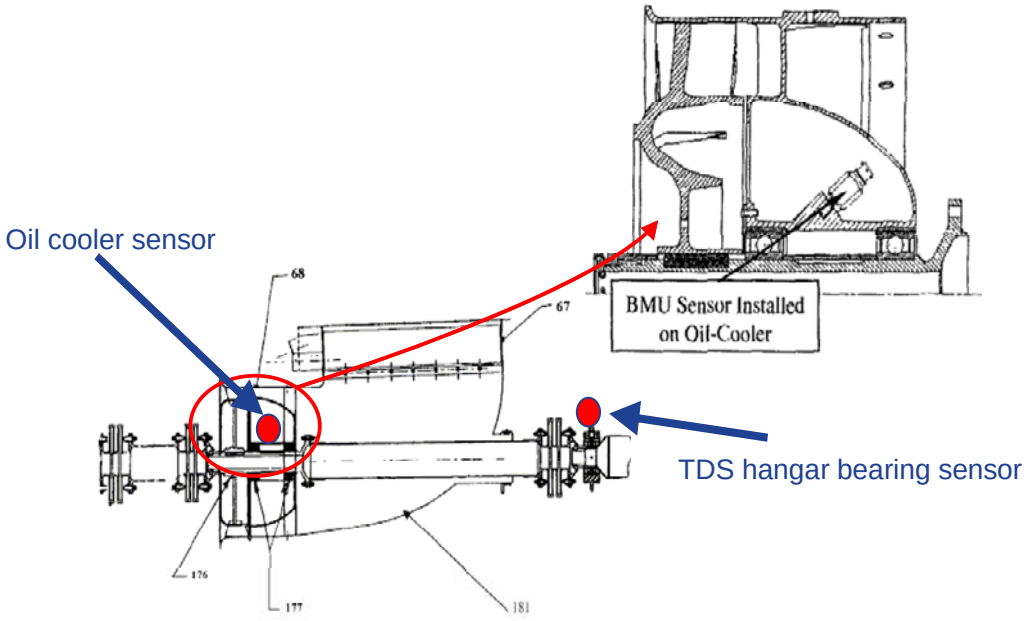


Figure 3. The BMS Sensors

The database contains the following BMS vibration measurements (OCBrg = oil cooler bearing, HgrBrg = hangar bearing).

- OCBrgBand0VibAvg (15- to 20-kHz average g)
- OCBrgBand1VibAvg (1.5- to 5-kHz average g)
- OCBrgBand2VibAvg (1/rev (64- to 73-Hz))
- HgrBrg1Band0VibAvg (15- to 20-kHz average g)
- HgrBrg1Band1VibAvg (1.5- to 5-kHz average g)
- HgrBrg1Band2VibAvg (1/rev (64- to 73-Hz))

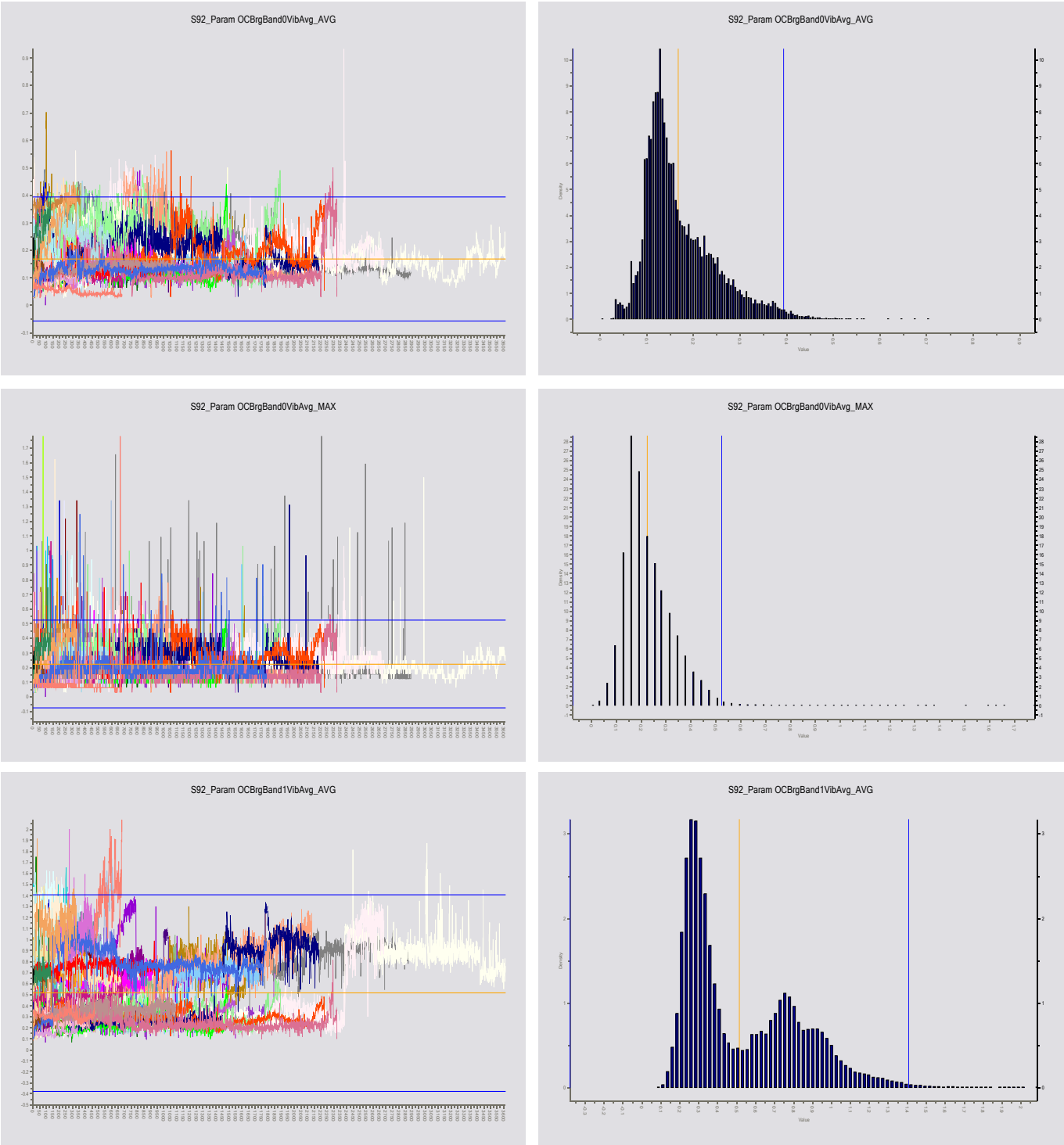
The database contained a set of HUMS flight records for each aircraft. Each HUMS flight record includes three statistics (MAX (maximum), AVG (average), and MIN (minimum)) to summarize six vibration measurements. Most of the analysis performed was based on the AVG data.

SAC also provided a database of S-92 maintenance actions related to oil cooler BMS alerts that are triggered by initial monitoring thresholds. The aircraft in this database were not identified. This database was used to analyze the findings from maintenance resulting from BMS alerts.

6.4.2 Statistical Analysis of the S-92 Oil Cooler HUMS BMS Data.

Fleet plots and histograms of the measurements OCBrgBand0VibAvg_AVG, OCBrgBand0VibAvg_MAX and OCBrgBand1VibAvg_AVG are shown in figure 4. The OCBrgBand0VibAvg_AVG data approximate to a skewed normal distribution. The OCBrgBand0VibAvg_MAX data is noisier, containing many isolated high value outliers. The histogram shows that the resolution of the MAX data is limited to multiples of 0.03125 (i.e., 1 divided by 32). The OCBrgBand1VibAvg_AVG data has a multimodal distribution, containing at least two clearly distinct distributions. This shows that that there are at least two groups of oil coolers generating distinctly different levels of Band 1 vibration under normal operating conditions. From a health monitoring perspective, this characteristic is undesirable as it is then difficult to set an appropriate monitoring threshold. This simple data exploration suggests that OCBrgBand0VibAvg_AVG provides the best behaved data for monitoring the OCBs.

To further investigate the statistical characteristics of the BMS data a correlation matrix was computed for the different BMS measurements. Figure 5 shows the correlation between each of the oil cooler and hangar bearing BMS frequency bands, based on the AVG measure. The figure shows a monochromatic scale that continuously varies with numeric values ranging from 1 to -1. The lighter and darker regions of the chart are intended to give an impression of the relative correlation of the parameters. White squares, such as those on the diagonal, show positively correlated data (correlation coefficient = 1), black squares show negatively correlated data (correlation coefficient = -1), and varying shades of gray represent everything in between, including data that are uncorrelated (correlation coefficient = 0).



Top = OCBrgBand0VibAvg_AVG
Middle = OCBrgBand0VibAvg_MAX
Bottom = OCBrgBand1VibAvg_AVG)

Figure 4. Fleet Plots and Histograms of Oil Cooler BMS Data

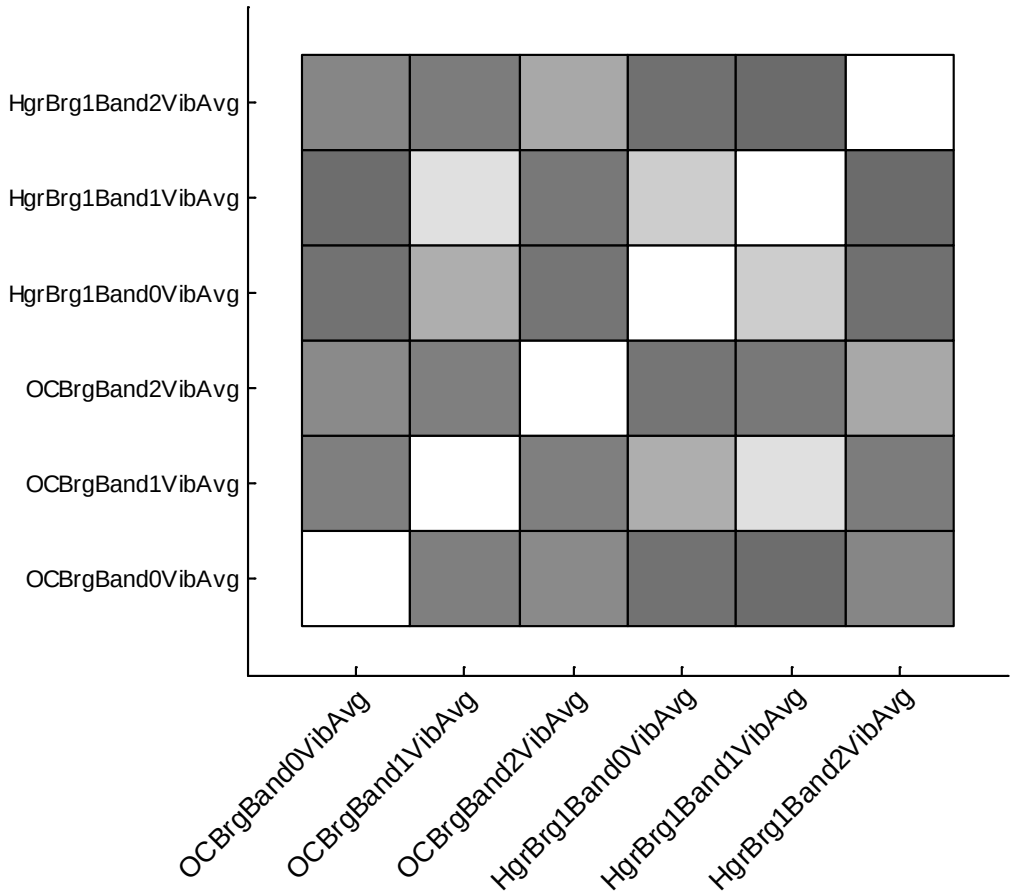


Figure 5. Correlation Matrix for the BMS Measurements

It is clear that there is some correlation between the two sets of Band 1 data collected from the oil cooler and hangar bearing, which is found to have a relatively high correlation coefficient of 0.745. Similarly, Bands 1 and 0 on the hangar bearing are reasonably correlated, with a correlation coefficient of 0.603. However, it is important to note that Bands 1 and 0 for the oil cooler are uncorrelated with a correlation coefficient of -0.001. SAC used Band 0 for monitoring the bearing health and Band 1 for monitoring the sensor health.

The correlation matrix suggests that

- the oil cooler BMS Bands 0 and 1 are measuring vibration from different components as the measurements are uncorrelated.

- the oil cooler BMS Band 1 is measuring vibration from the drive train components, other than the OCBs, as that oil cooler Band 1 data are reasonably well correlated with the Band 1 data from the hangar bearing BMS.

- the oil cooler BMS Band 1 data are, therefore, an unreliable indicator of the health of the OCBs. In the S-92 fleet this band is used to check sensor health.

In concurrence with SAC's monitoring techniques, the statistical analysis shows that only the oil cooler BMS Band 0 data can reliably be used for monitoring the health of the OCBs. This conclusion is supported by a simple consideration of the system physics. The S-92 drive train contains many more sources of vibration in the 1.5- to 5-kHz-frequency range (Band 1) than in the 15- to 20-kHz range (Band 0), for example, components such as gears and accessories. In addition, vibration attenuates more rapidly at a high frequency than at a low frequency as it travels through a structure. Therefore, provided the BMS is mounted close to the OCBs, the high-frequency data were more likely to originate from these nearby components.

6.4.3 Anomaly Modeling of HUMS BMS Data.

GE Aviation's advanced HUMS anomaly detection system was used to build anomaly models for the oil cooler data. Multivariate models are normally built by fusing the data from multiple HUMS CIs to identify anomalous combined indicator trends. However, univariate models can also be built that provide robust statistical modeling of the behavior of a single HUMS CI. The conclusions from the statistical analysis described in section 6.4.2 are that the oil cooler BMS Bands 0 and 1 measurements are uncorrelated, and Band 1 may be measuring vibration from drive train components other than the OCBs. Therefore, in this particular case, multivariate models fusing data from Bands 0 and 1 were considered to be of limited benefit for monitoring the health of the OCBs, and more use has been made of univariate models.

Before being input to an anomaly model, the data were preprocessed by applying a median filter to clean the time history data by removing up to two consecutive outliers. A trend extraction algorithm can be applied in the second stage of preprocessing to enable models to be built to detect anomalous data trends. However, although a set of trend models were built, the results from these were not included in this report.

Seven anomaly models were initially constructed for the BMS vibration data, with the following different input parameters:

- Model 1 OCBrgBand0VibAvg_AVG
- Model 2 OCBrgBand0VibAvg_MAX
- Model 3 OCBrgBand1VibAvg_AVG
- Model 4 OCBrgBand1VibAvg_MAX
- Model 5 OCBrgBand0VibAvg_AVG, OCBrgBand1VibAvg_AVG
- Model 6 OCBrgBand0VibAvg_MAX, OCBrgBand1VibAvg_MAX
- Model 7 OCBrgBand0VibAvg_AVG, OCBrgBand0VibAvg_MAX

Corresponding models based on the hangar bearing data were also produced; however, these were used solely to support the analysis of the oil cooler data, and the results are not presented here.

The anomaly modeling process incorporates automated filtering, controlled by a tuning parameter, to remove data during model training that the process considers to be anomalous. This allows models to be built on in-service data containing some anomalies and prevents these from masking later anomalies that should be detected. By varying the tuning parameter, the

sensitivity of the models can be adjusted. A default tuning parameter setting was used in all cases, and no specific model tuning was performed.

There are two outputs from each model:

1. A fitness score showing how well the data fit the model of normality (this score decreases as data becomes more anomalous, as the goodness of fit to normality decreases)

2. A probability of anomaly (PA) (a probability that data are anomalous with a normalized range of 0-1)

The output PA values were postprocessed to generate alerts, with an alert being triggered when 3 out of 4 PA values exceeded a threshold of 0.9.

6.4.4 Correlation of Anomaly Modeling Results With Oil Cooler Maintenance Actions.

The analysis of the anomaly modeling results was limited to the models built using the Band 0 data and specifically to the results from models 1 and 7. Model 1 is a univariate model with OCBrgBand0VibAvg_AVG as the input variable, and model 7 is a bivariate model with the two inputs of OCBrgBand0VibAvg_AVG and OCBrgBand0VibAvg_MAX.

Of the 27 cases of maintenance actions related to BMS alerts in the SAC database, 7 cases were repeat occurrences on the same aircraft (but, in some cases, with different oil coolers fitted) within 1 month of each other. Therefore, there were 20 independent cases on different aircraft or on the same aircraft separated by more than 1 month. Of these 20 cases with a PA threshold of 0.9, only 3 produced an alert from anomaly model 1, and 5 produced an alert from model 7. For one of the cases, triggering an alert on model 1 did not alert on model 7; therefore, together, the two models triggered an alert on 6 of the 20 cases. Due to the robust statistical modeling performed in the model-building process, for 14 cases of maintenance actions related to BMS alerts, the anomaly models did not trigger an alert. Because no developing bearing damage was found in any of the cases, this indicated that the initial BMS thresholds were too low (the initial Band 0 threshold of 0.5 g has since been raised to 0.75 g). Models 1 and 7 also produced alerts for two cases that were not in the SAC database of maintenance actions. Based on dates of these alerts, SAC concluded that the cases were early in the lives of the respective oil coolers and could be attributed to an initial break-in period.

6.4.5 Exploration of S-92 Data.

The rig test data were explored to verify the quality of the acquired data and to characterize the test rigs used for Phases 1 and 2, identifying any rig features that could affect comparison of the results with aircraft data.

All the data from Phase 1 oil cooler fan test rig and the data from test 1 of the Phase 2 tests were compared. Phase 1 oil cooler fan rig test data consisted of ten different bearing tests with two data bursts captured per test. Test 1, Phase 2 involved running the S-92 oil LTF bearings in a different S-92 oil cooler fan test rig. This resulted in nine different bearing tests with four data bursts captured per test. Fast Fourier Transforms (FFT) were calculated for each burst of each

test and compared. It was noted that the Phase 1 rig had a hydraulic drive, and the Phase 2 rig was driven by an induction motor, which may have different vibration characteristics.

The following points summarize the findings of this analysis:

- The first three shaft orders (SO) and SO21 (fan blade pass frequency) were almost always present in all tests. This confirmed that the expected tones were present and the data were good.

- In addition, the imbalanced tests in Phase 1 usually had SO4-13 and higher fan frequencies (SO42, SO63, and SO84) clearly visible.

- All Phase 2 tests had the same shaft speed (68.7 Hz). The Phase 1 tests varied from 68.4 to 69.6 Hz. The variance in speed affected the position of all tones, but could be accounted for in the analysis.

- Phase 2 data generally had slightly higher energy than Phase 1.

- Phase 1, test 8 (LTF 4) had very low energy above 5 kHz. The test was repeated in Phase 2 and results showed good correlation. Phase 2 LTF 1 had generally higher energy than the other Phase 2 LTF bearings; this can be attributed to a lack of grease. Sentient noted that this bearing was very low on grease and repeated the test with sufficient grease present. Values were reduced to expected levels.

- At approximately 10 kHz, a broad peak in energy was apparent for Phase 2 LTF 2 and LTF 7 and all Phase 1 tests except 6 and 8. These energy peaks may relate to structural resonance of the test rigs.

- The Phase 2 tests appeared to have sideband-like features approximately 37.2 Hz on either side of SO1, SO2, SO3, and the blade pass (SO21, SO42, SO63, and SO84). It is not known what caused these features. None of the tones corresponded to any defect frequencies of the bearings; this may relate to Phase 2 test rig using an induction motor.

- Each burst for each test had similar features present. 70% of the Phase 1 tones identified were found in both bursts. For Phase 2, 41% of the tones identified were found in all four bursts, and 78% were found in two or more bursts.

- Most of the Phase 2 tests had low-energy tones at exactly 5, 10, 15, and 20 kHz. This is most likely a result of the test setup and did not affect the overall results.

Figure 6 shows an example FFT from each phase with the above findings labeled where present.

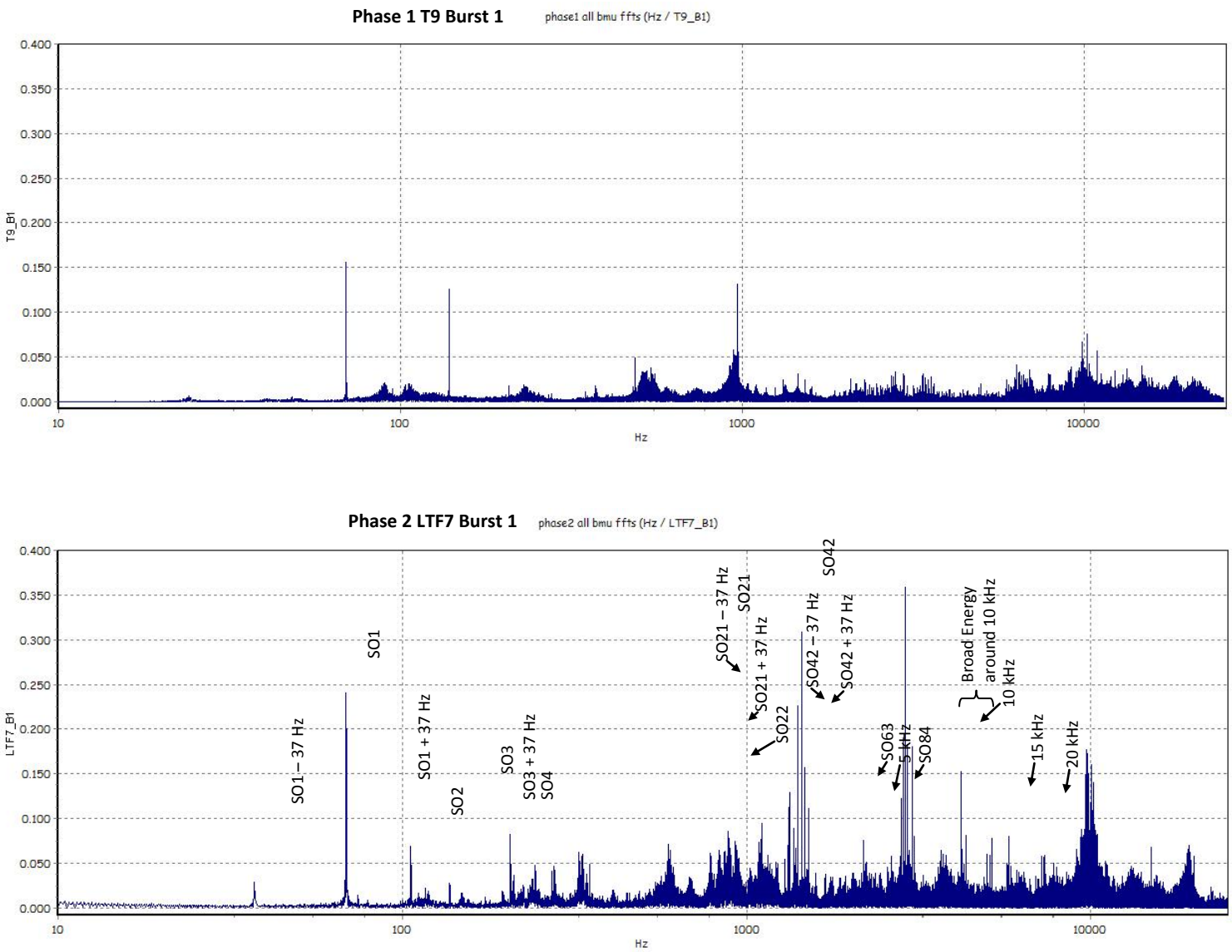
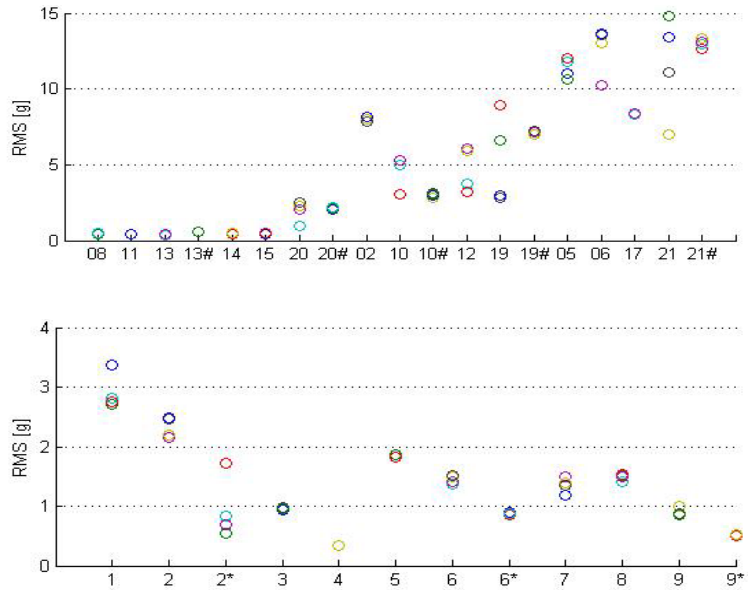
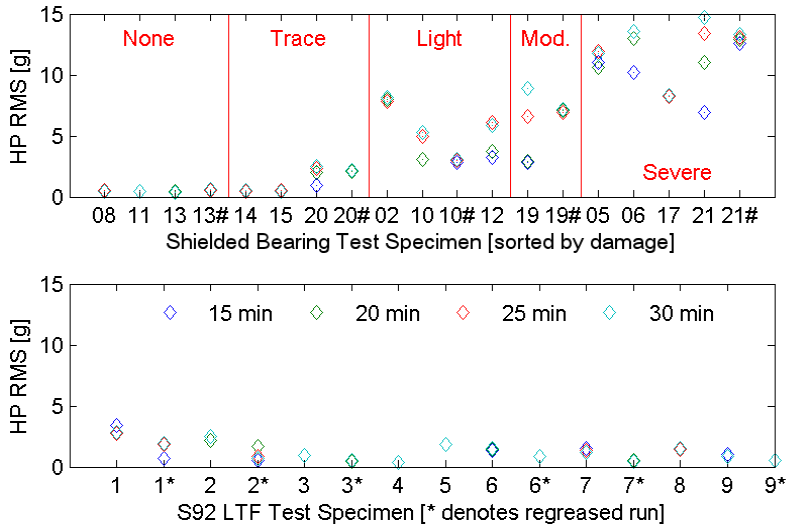


Figure 6. Key Features on Example FFTs From Phases 1 and 2

Figure 7 shows the high-pass (HP), filtered (15- to 40-kHz) root mean square results for the shielded bearings and the S-92 LTF sealed bearings used in test 1 of Phase 2. Bearing designs were otherwise comparable. The Sentient Phase 2 test results from their report are shown on the right, and GE Aviation results are shown on the left. The results were found to be exactly the same, which gives confidence in both the data and the analysis.



(a)



(b)

Figure 7. Comparison Between GE Aviation (a) and Sentient (b) Results

A further check was made between the LTF bearings from both phases. The raw BMS sensor data were processed using the BMS analysis technique performed onboard the aircraft to enable it to be compared to the aircraft data. The results are shown in table 7. Phase 1 results are

shown at the top of the table, including two bursts and the mean. The Phase 2 results are shown below; first, comparing the forward bearing, and then the aft bearing, since in Phase 2 each LTF bearing was run with a "dummy" bearing. Again, the four bursts and a mean are shown. The percentage differences between the means are shown. When the differences are within 25%, it is marked as a match, otherwise it is flagged in red and indicated as being high or low compared to the Phase 1 results. The means are plotted in figure 8. Because there were differences between the bearing configurations tested, and potentially, in the lubrication state of the bearings, the results were not expected to closely match. However, a very good level of consistency was achieved. The aft bearings match very well except for LTF 1, and the forward bearings match well except for LTF 5. (The LTF 1 result appears anomalous and could be due to the "dummy" bearing running in the forward position.)

Table 7. Comparison Between Phases 1 and 2 LTF Bearing BMS Results

Phase 1 BMS HP Band Averages					
Test	#03B	#05	#07	#09	#11
FWD Bearing	8841	5785	5811	5793	5796
AFT Bearing	8844	5801	5802	5796	5793
Burst 1	0.2051	0.1759	0.1256	0.3504	0.2523
Burst 2	0.1981	0.1749	0.0931	0.3653	0.2730
Mean	0.2016	0.1754	0.1093	0.3578	0.2627
Phase 2 Comparison					
Test	#03B	#05	#07	#09	#11
Bearing (FWD in Phase 1)	LTF 5	LTF 3	LTF 4	LTF 6	LTF 7
Burst 1	0.3865	0.1902	0.0675	0.2774	0.2969
Burst 2	0.3902	0.1888	0.0643	0.2820	0.2736
Burst 3	0.3772	0.1808	0.0646	0.2998	0.2668
Burst 4	0.3661	0.1888	0.0650	0.3010	0.2301
mean	0.3800	0.1871	0.0654	0.2900	0.2669
Match (mean)	High	Match	Low	Match	Match
	88%	7%	-40%	-19%	2%

Table 7. Comparison Between Phases 1 and 2 LTF Bearing BMS Results (Continued)

Phase 2 Comparison					
Bearing (AFT in Phase 1)	LTF 8	LTF 9	LTF 1	LTF 7	LTF 6
Burst 1	0.2300	0.2037	0.5861	0.2969	0.2774
Burst 2	0.2331	0.1763	0.5096	0.2736	0.2820
Burst 3	0.2105	0.1748	0.5233	0.2668	0.2998
Burst 4	0.2160	0.1747	0.5286	0.2301	0.3010
mean	0.2224	0.1824	0.5369	0.2669	0.2900
Match (mean)	Match	Match	High	Match	Match
	10%	4%	391%	-25%	10%

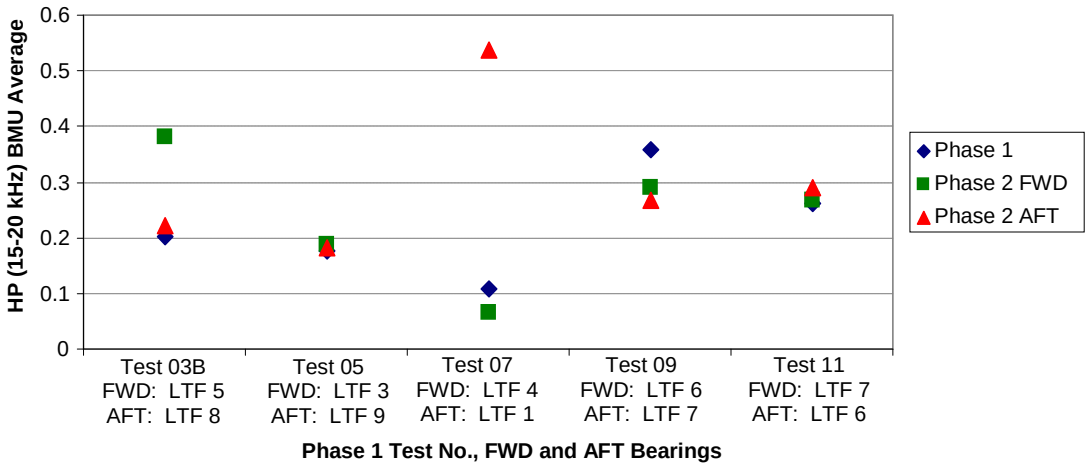


Figure 8. Comparison Between Phases 1 and 2 LTF Bearing BMS Results

Statistics of the rig test data for the LTF as-received bearings were computed and compared to the fleet data, as shown in table 8. The statistics show that the data from the two phases compare favorably with the fleet data. For example, the means for Band 0 are all very consistent at approximately 0.2, and the means for Band 1 are all between 0.35 and 0.51.

Table 8. Data Statistics

Data Description	Mean	Standard Deviation	Mean +3 Standard Deviation
Fleet Band 0 Avg	0.17	0.08	0.39
Phase1_Band0	0.18	0.11	0.51
Phase2_Test1_LTF_Band0	0.25	0.14	0.67
Fleet Band 1 Avg	0.51	0.30	1.41
Data Description	Mean	Standard Deviation	Mean +3 Standard Deviation
Phase1_Band1	0.35	0.23	1.04
Phase2_Test1_LTF_Band1	0.41	0.20	1.01

6.4.6 The BMS Analysis.

To use the rig test data to set thresholds and show fault detection, it must be compared to the aircraft data. To do this, the BMS analysis performed onboard the aircraft must be replicated as closely as possible.

6.4.6.1 Results.

The analysis of the BMS results from Phase 2, test 5, which has an extensive amount of data bursts, showed that there were only relatively small variations between the different bursts for each bearing.

Figure 9 shows the BMS analysis results for burst two from all tests and all phases for the two passbands (PB) from the BMS sensor. Similar results were observed with the average of all the bursts for each test. The current HP (Band 0) threshold is 0.75 g (increased from an initial value 0.5 g). Using this threshold and the average HP value for all the bursts, the shielded bearings with light damage or above would trigger alerts (apart from bearing 10 in the aft position). The Phase 2, test 2 bearing with assembly damage caused by a 15,000-lb load would also trigger an alert. If the threshold was set at the initial value of 0.5 g, the Phase 2, test 5 LTF 6 bearing degreased runs would all trigger alerts. However, this value would also cause alerts in the fleet data, which are known to be from healthy bearings. This PB responded to the degreased bearings better than the low-pass (LP) data, showing greater sensitivity to lubrication condition. It also responded to the lower levels of assembly damage (test 2) and minor spalls (test 4), but values were still below 0.5 g. However, this indicated that if these faults were more severe, the data would likely trigger an alert. Relative to the shielded bearings, the spalls on the S-92 bearings would start at a trace level and then, after running in the bearing rig, increase only to light levels, which do not require maintenance action. Even at light levels, an increasing vibration trend was observed (test 4). In test 5, vibration levels increased when the spalled bearing was degreased, but were still just below the 0.75 limit. Since the cage crack (test 3) and degreased runs (test 5) did not get worse with time, they could be considered fault-free cases, or

at least early stages of degradation, and so should not be alerted by the HUMS. Hence, the results of the BMS analysis can be considered to be very good, with all major faults identified.

Using the LP (Band 1) data and a threshold of 0.75, again the shielded bearings with light damage or above would trigger alerts. In addition, the Phase 2, test 2 bearings with assembly damage caused by a 10,000-lb load or more and the Phase 2, test 4 bearings with minor spall damage, triggered alerts. All other tests (apart from Phase 1, test 6 and Phase 2, test 1 LTF 1) have BMS averages below this threshold. Again, since the cage crack (test 3) and degreased runs (test 5) did not get worse with time, they could be considered as fault-free or early-stage degradation cases and, therefore, should not be alerted by the HUMS. Hence, this result would be very good, with all faults identified and only two potential false alarms. However, as discussed in the previous section, this PB is primarily used for checking sensor health and is unreliable for monitoring an installed bearing; and this threshold would cause many alerts if applied to the fleet data supplied.

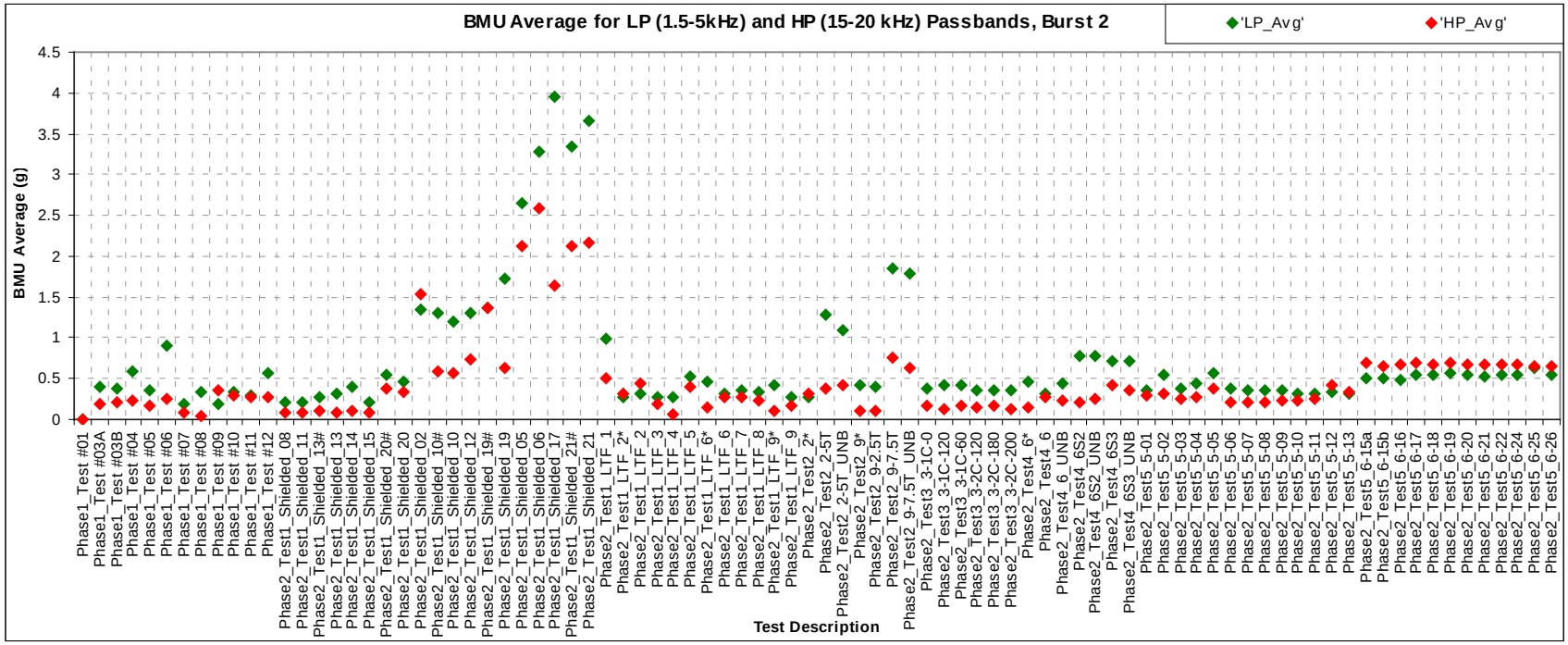


Figure 9. The BMS Averages for Burst 2 for All Phases and Tests

6.4.6.2 Detection Matrix.

To make a more analytical assessment, a detection matrix was used to statistically compare the results. Table 9 shows the fault detection matrix. The matrix indicates the following four possible outcomes for each test case:

- Fault occurs and alert is initiated (positive)
- No fault occurs, but alert is initiated (false positive)
- Fault occurs, but alert is not initiated (false negative)
- No fault occurs, and alert is not initiated (negative)

The goal is to detect all faults, while having no false alerts. An accuracy measure can then be computed by summing the positive and negative results and dividing by the total number of cases. This is shown in table 10.

Table 9. Fault Detection Matrix

Outcome	Fault	No Fault	Total
Alert	*a* detected faults (positive)	*b* false alerts (false positive)	*a* + *b* total alerts
No alert	*c* missed fault (false negative)	*d* correct rejection (negative)	*c* + *d* Total no alerts
Total	*a* + *c* number faults	*b* + *d* number no faults	*a* + *b* + *c* + *d* number cases

$$accuracy = \frac{a+d}{a+b+c+d} \tag{1}$$

Table 10. The BMS Detection for Each Passband and Different Thresholds

Passband (kHz)	Threshold	False Negative (%)	False Positive (%)	Negative (%)	Positive (%)	Accuracy (%)
LP: 1.5 to 5	0.75	15.8	3.9	96.1	84.2	90.1
HP: 15 to 20	0.75	52.6	0.0	100.0	47.4	73.7
LP: 1.5 to 5	1.00	27.6	2.4	97.6	72.4	85.0
HP: 15 to 20	0.5	32.9	22.0	78.0	67.1	72.5

To apply this methodology to the data, each case must be designated a state of fault or no fault. The cracked cage and the degreased bearings were not marked as faults. Although these would be considered abnormal conditions, the bearing continued to function satisfactorily.

In addition to defining the fault cases, each analysis method must produce alerts. For this comparison, two thresholds for each PB are compared. The ideal method should have 0% false negatives and positives, and 100% negatives and positives, giving 100% accuracy. As expected, the LP (Band 1) results with a threshold of 0.75 gave the best accuracy (90.1%); however, this produced large numbers of false alerts in the field and was shown to have interference from other vibration sources. Using the HP (Band 0) data with the current threshold of 0.75 gave an overall accuracy of 73.7%. There were no false alerts, but approximately half the seeded faults were not detected at the severity level tested. However, the tests showed that none of the undetected faults required immediate maintenance; therefore, the tests represent an evaluation of early-stage detection capabilities. It was expected that more significant damage requiring maintenance intervention would be detected; however, further evidence is needed to verify that.

6.4.6.3 The HUMS BMS Conclusions.

The analysis of the BMS data showed that the rig test data can be compared directly with the aircraft data. Performing the current BMS analysis techniques on the rig test data allowed very good fault detection using the Band 1 (LP, 1.5- to 5-kHz) frequencies and a threshold of 0.75; however, this caused excessive false alerts in the fleet data, which was shown to contain vibration from other sources. Using Band 0 (HP, 15- to 20-kHz) frequencies and the current threshold of 0.75, there were no false alerts, and the seeded faults detected at the damage levels tested were the corroded, shielded bearings and the assembly damage at 15,000-lb load. The light spalls and lesser assembly damage faults remained undetected at the early stage. However, based on the increasing vibration trends relative to spalling damage (from trace to light spalls to degreased) and the level of corrosion tested, it would be expected that a moderate spall would be detected. If the threshold was set at the initial value of 0.5 to improve sensitivity, the Phase 2, test 5 LTF 6 degreased runs would all triggered alerts. However, this value also caused alerts in the fleet data, which are known to be healthy. The BMS temperature data, although useful for a late indication of bearing failure, was not able or expected to give early indications of any of the faults tested.

When interpreting these results, apart from the corroded, shielded bearings, the damage levels tested can be considered to be well below those that could result in a bearing failure. This highlights the limitations of seeded fault testing in generating evidence for CBM credit validation. The results do show, however, the ability of the BMS measurements to respond to bearing damage.

6.4.7 Passband Investigation.

One change that could be made to the current BMS, which might affect fault detection, would be to adjust the PB frequencies. To investigate this, the BMS analysis was applied using four octave PBs (i.e., PB3: 0-5 kHz, PB4: 5-10 kHz, PB5: 10-20 kHz, and PB6: 20-40 kHz). Figure 10 shows the results of applying the BMS analysis to the BMS sensor data for all tests using these octave PBs. The results in the chart are averaged over all bursts. For the Phase 1 data, the 20- to 40-kHz band could not be calculated due to the lower sample rate used. However, it is worth noting that the onboard system currently samples at a rate that would not allow frequencies over 25 kHz to be analyzed. The chart shows that the different PBs all have

similar trends, and it is difficult to judge which PB performs the best. Note that PB6 has been plotted on a secondary axis since the amplitudes are significantly lower than the other PBs.

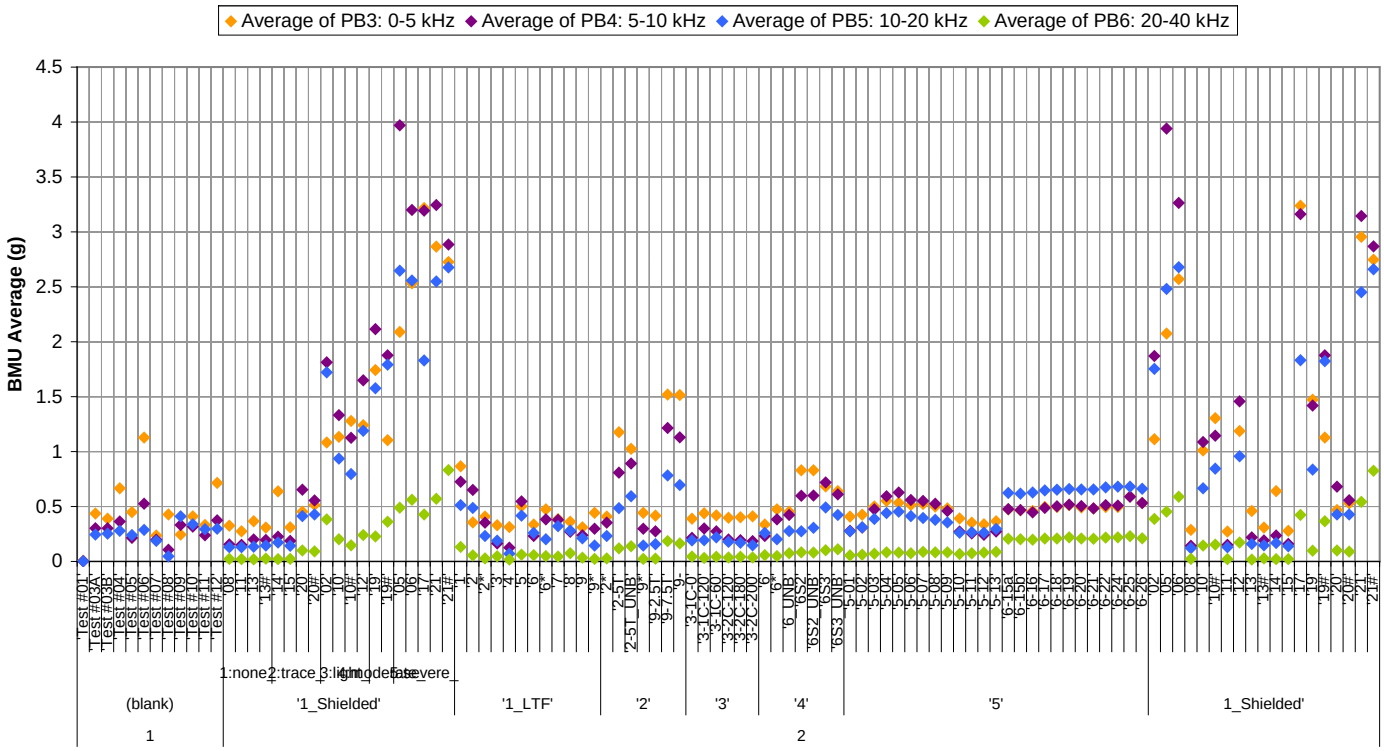


Figure 10. The BMS Averages, Octave Passbands

To make a more analytical assessment the detection matrix described in section 6.4.6.2 was used to statistically compare the results. A threshold of 0.75 was used for all PBs except the 20- to 40-kHz PB, for which a value of 0.25 was used. Table 11 shows the results as a percentage of the number of fault/nonfault cases. Again, the PBs below 5 kHz performed the best; but on aircraft, these are known to be affected by vibration from other components. In addition, if the threshold on these PBs was increased to 1.5 (which would be required to reduce false alarms in the field), their accuracy would drop to about 68%, which is below the higher PBs. The 5- to 10-kHz band is the next best; however, it is not known whether these frequencies would also be affected by other vibration sources on aircraft. The 10- to 20-kHz PB gives a slightly higher accuracy than the 15- to 20-kHz BMS PB.

Table 11. The BMS Detection for Comparing Passbands

Passband (kHz)	Threshold	False Negative (%)	False Positive (%)	Negative (%)	Positive (%)	Accuracy (%)
PB1: 1.5 to 5	0.75	15.8	3.9	96.1	84.2	90.1
PB2: 15 to 20	0.75	52.6	0.0	100.0	47.4	73.7
PB3: 0 to 5	0.75	15.8	3.9	96.1	84.2	90.1
PB4: 5 to 10	0.75	27.6	3.5	96.5	72.4	84.4
PB5: 10 to 20	0.75	39.5	0.0	100.0	60.5	80.3
PB6: 20 to 40	0.25	57.9	0.8	99.2	42.1	70.7

6.4.8 The GE Aviation Generic HUMS Bearing Analysis.

The generic HUMS (GenHUMS) bearing vibration analysis process consists of two elements. In the primary analysis, the acquired vibration data (SIG) is band-pass filtered, the filtered signal is enveloped, and the enveloped signal (ETE) is then converted into the frequency domain to produce an envelope power spectrum (FTE). Secondary analysis involves the calculation of a series of CIs at different stages of the primary analysis process. The CIs include pattern match indicators that search for defect patterns associated with damage on a bearing inner race (IN), outer race (OU), cage (CG), and rolling elements (EL). Figure 11 shows the frequencies and pattern match weights used in this analysis for the S-92 bearings.

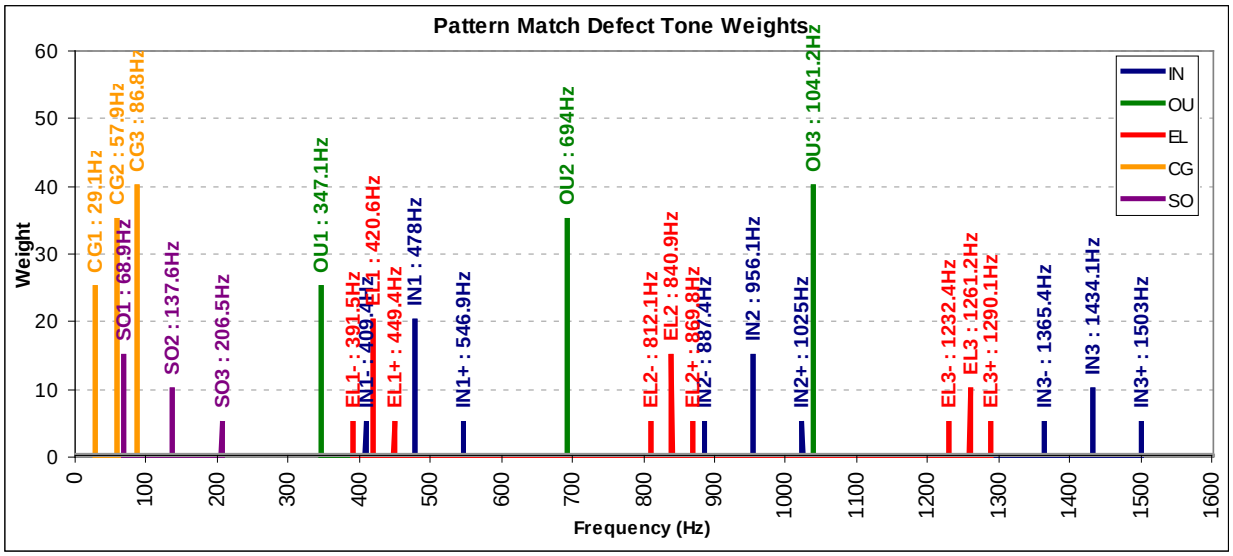


Figure 11. Defect Tone Frequencies and Pattern Match Weights for the S-92 Bearing

The GenHUMS PBs were configured for the two BMS bands (1.5 to 5 and 15 to 20 kHz) and four octave PBs (0 to 5, 5 to 10, 10 to 20, and 20 to 40 kHz). The CIs that were calculated are listed in table 12. Different analysis configurations were required for the S-92 and shielded bearing geometries.

Table 12. The GenHUMS Bearing CIs

GenHUMS CI	Description
SIG_PP	Peak-to-peak, difference of the maximum and minimum
SIG_PK	Peak, maximum absolute data value
SIG_MN	Mean of the data
SIG_STD	Standard deviation of the data
SIG_MRC	Max Rate of Change, Maximum absolute difference of adjacent data values
FTE_EB	Energy of the band-passed envelope spectrum
FTE_TON	Tonal energy of the band-passed envelope spectrum
FTE_WHT	White-noise energy of the band-passed envelope spectrum
FTE_IN	EI for tone pattern generated by inner race damage
FTE_ID	DI for tone pattern generated by inner race damage
FTE_OU	EI for tone pattern generated by outer race damage
FTE_OD	DI for tone pattern generated by outer race damage
FTE_EL	EI for tone pattern generated by rolling element damage
FTE_ED	DI for tone pattern generated by rolling element damage
FTE_CG	EI for tone pattern generated by cage damage
FTE_CD	DI for tone pattern generated by cage damage
ETE_M6	Measure of impulsiveness of the enveloped time signal
FTH_SO01	Magnitude of first SO vibration
FTH_SO02	Magnitude of second SO vibration

EI = Energy index
DI = Detection index (0%-100%)

6.4.8.1 Results.

All the rig test data were run though the GenHUMS algorithms. A total of 38,440 CIs were calculated: for Phase 1, 10 tests and two bursts, and for Phase 2, 73 tests and four bursts, each across six PBs. Eleven CIs were calculated with no PB, and seventeen CIs for the PB signal. Figure 12 shows the results for FTE_EB. Similar results were observed for the other CIs. The charts allow the various PBs and bursts to be compared across all data. FTE_EB is the CI that most closely matches the current BMS analysis. Figure 12 clearly shows how the high-damage, shielded bearings have high energies, as does the Phase 2, test 2 bearing, which had significant assembly damage. The chart also has a black line indicating the average of the bursts and Pbs; this average can be used to create simplified charts to compare CIs, as shown in figure 13. Most of the charts for the other CIs had a shape similar to figure 13, with the high-damage, shielded bearings and assembly damaged bearings having high-CI values.

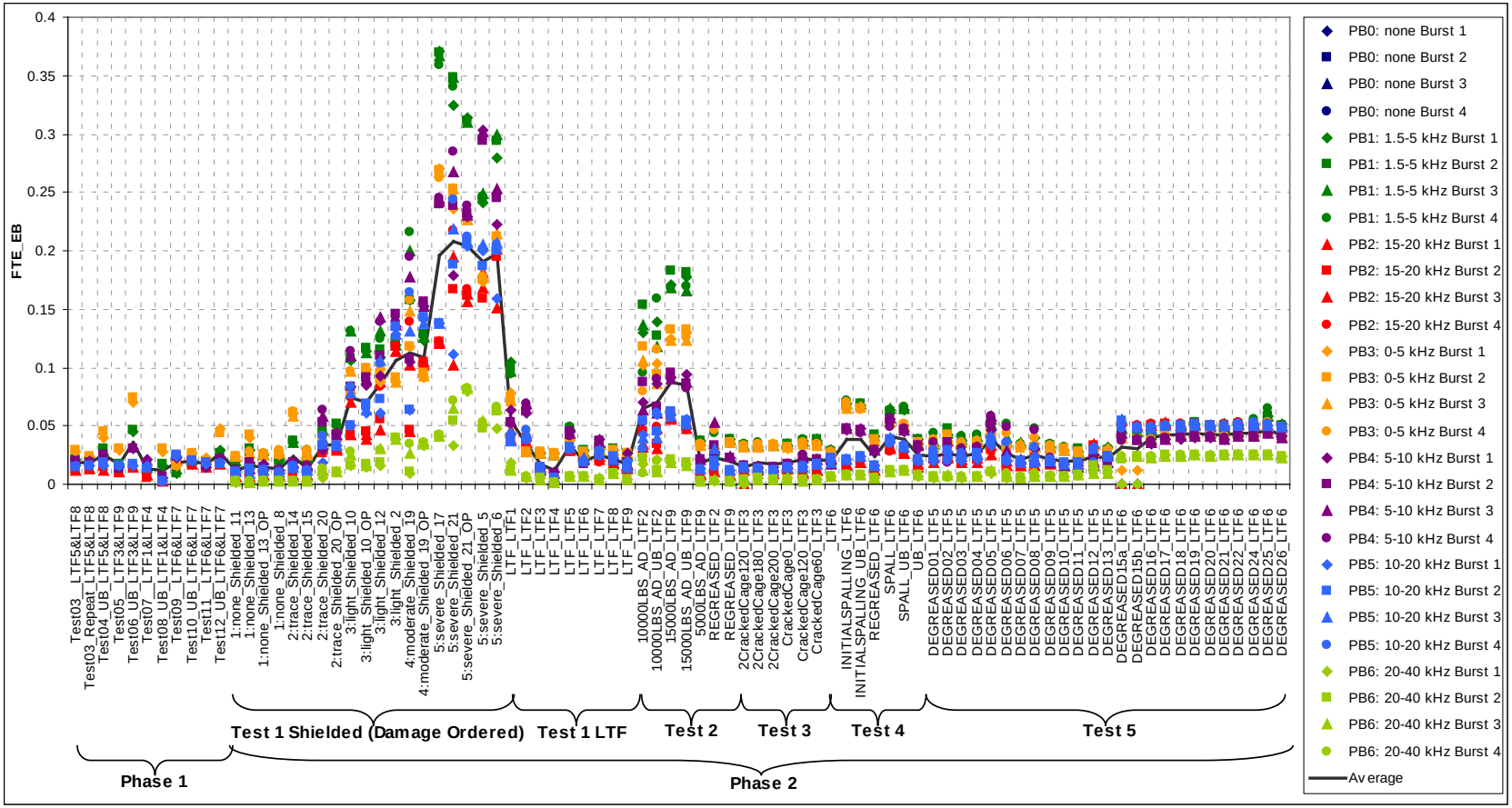


Figure 12. The FTE_EB CI Values for All Phases 1 and 2 Data (All bursts, six PBs)

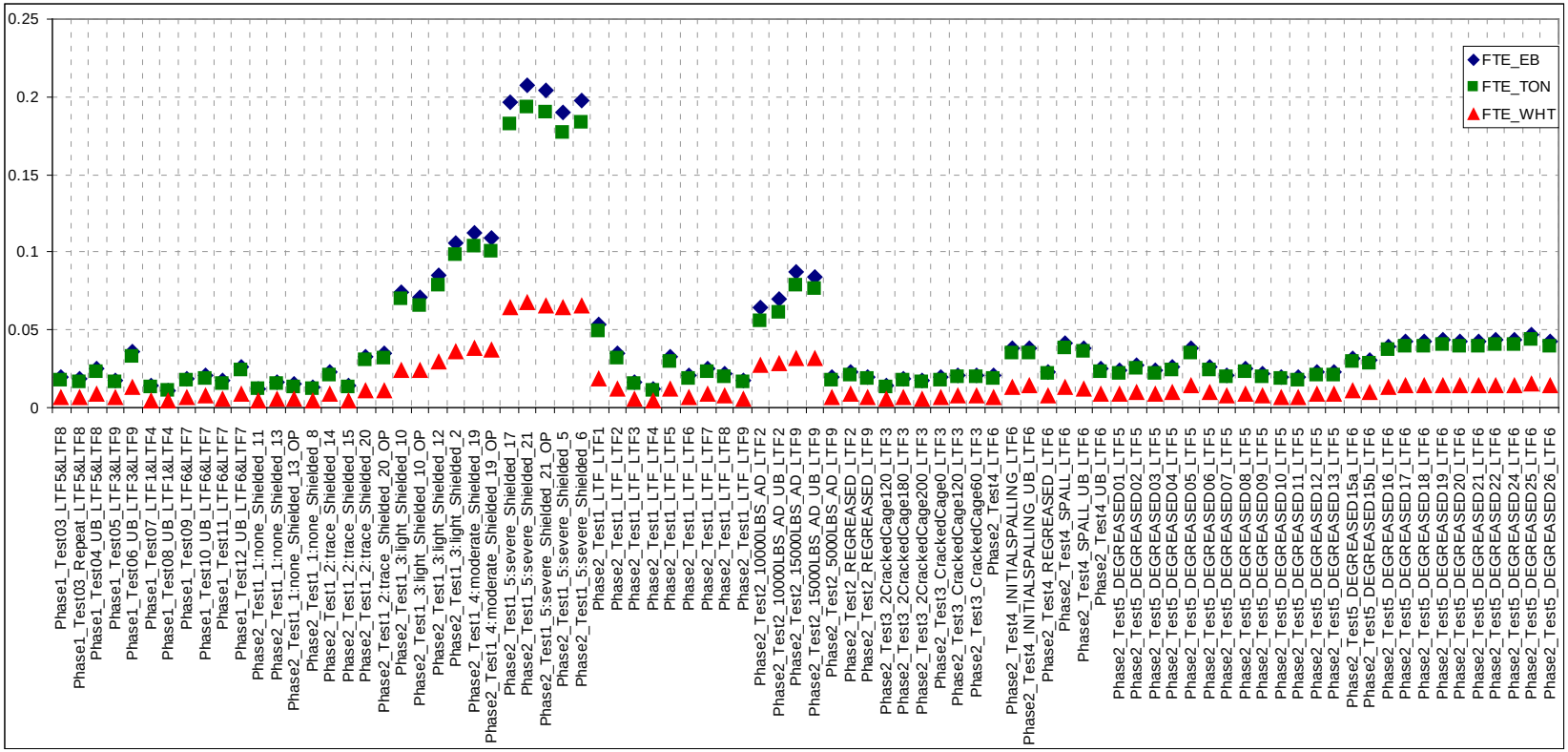


Figure 13. Energy CIs—Averaged Across All Bursts and PBs

Figure 14 shows the averaged pattern match defect indicators. Values under a threshold of 30% can usually be ignored. The indicators show good results, with low pattern scores for the as-received bearings and high pattern scores for

- rolling element defects for test 2 LTF 2 with 10,000-lb damage.
- cage defects for test 2 LTF 9 with 15,000-lb damage.
- inner race defects for test 4 LTF 6 with spall damage.
- various high values for high-damage, shielded bearings—see table 13.

Table 13. Average Pattern Match Defect Indicators for the Shielded Bearings

Damage Rating	Bearing	Average of FTE_CD	Average of FTE_ED	Average of FTE_ID	Average of FTE_OD
1: None	8	3	0	2	4
	11	0	0	0	1
	13	0	1	1	1
	13*	31	1	0	1
2: Trace	14	0	1	1	0
	15	5	2	3	3
	20	44	29	12	75
	20*	67	2	13	96
3: Light	2	41	49	47	55
	10	27	15	66	33
	12	3	23	71	40
	10*	6	4	69	8
4: Moderate	19	0	11	18	42
	19*	1	13	19	16
5: Severe	5	0	1	0	0
	6	7	7	46	65
	17	7	16	26	9
	21	7	13	74	40
	21*	9	3	41	80

*Bearing fitted in outlet position. Values over 30 are shown in red.

Figure 15 shows a heat map of all the averaged CIs for comparison (they have been normalized to a scale of 0 to 1, and M6 CI was logged). It shows that most CIs responded to the damaged bearings and to the bearing with assembly damage. The pattern match indicators also allowed the spalled bearing to be identified. Most CIs also responded slightly to the degreased bearing. As expected, the cage crack did not appear to affect the bearing vibration at all.

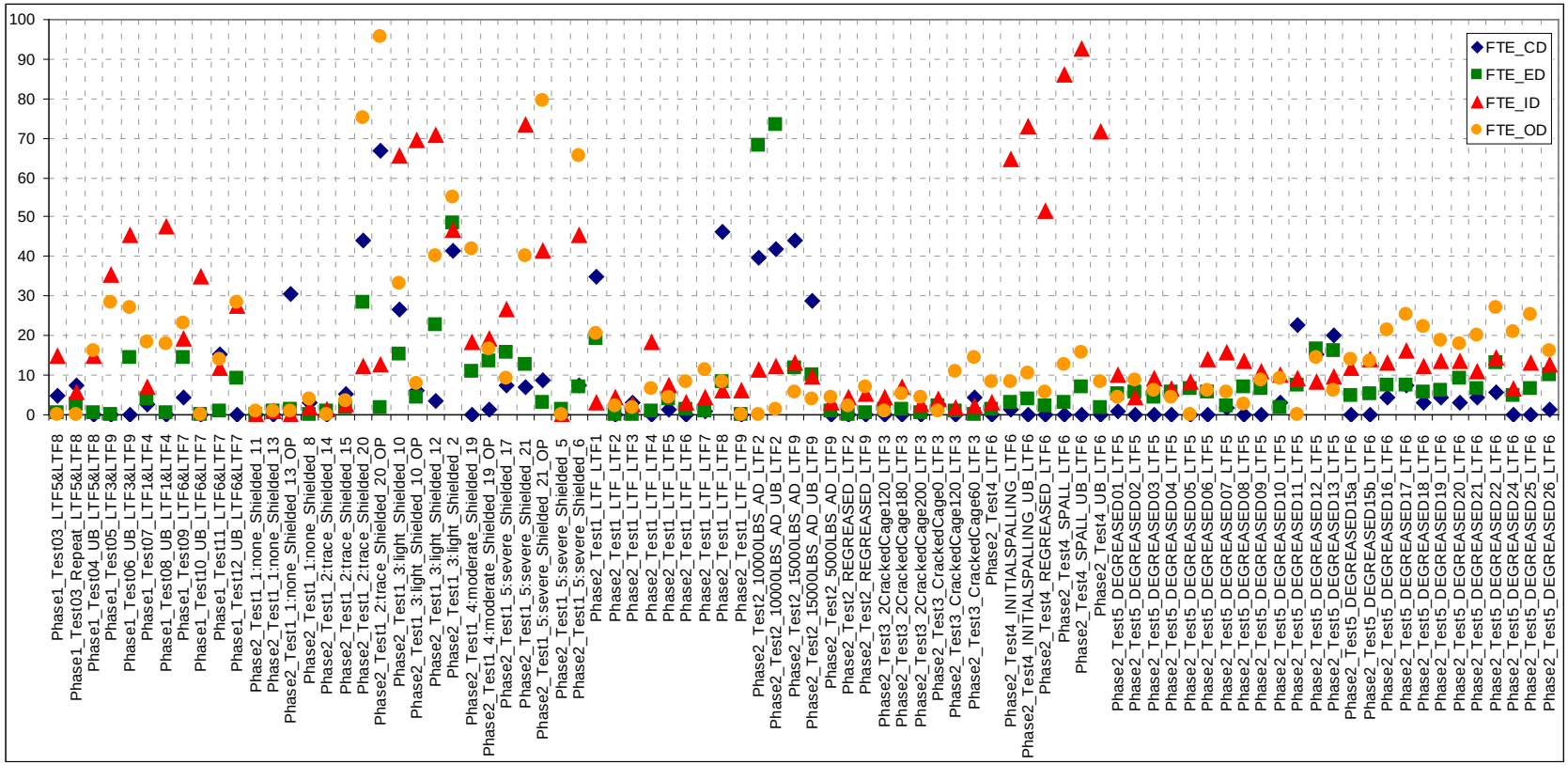
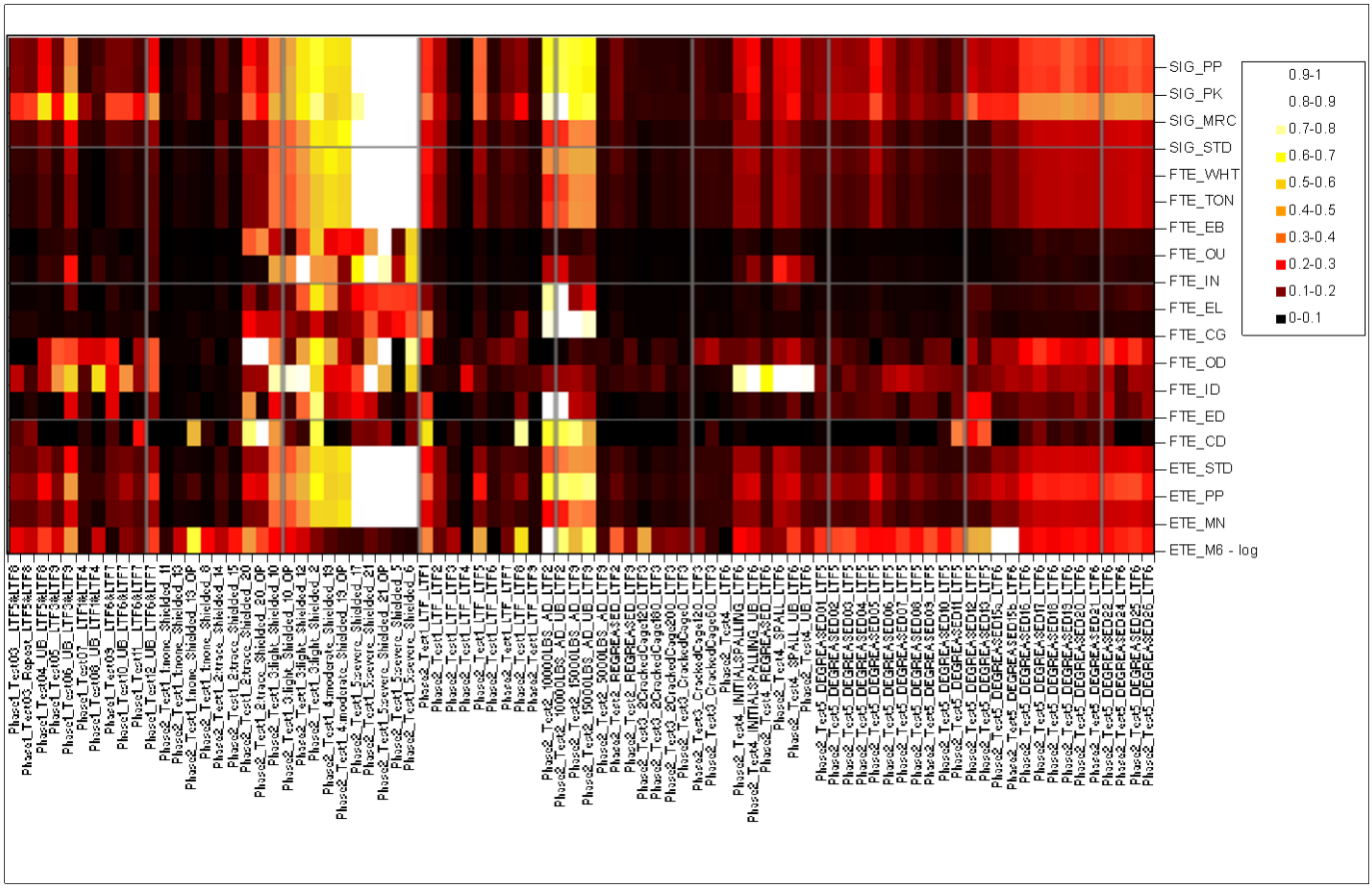


Figure 14. Pattern Match Defect Indicator Averages



(Averaged across bursts and PBs, M6 logged, then normalized from 0 – 1)

Figure 15. Heat Map Showing Response of CIs From Each Test

6.4.8.2 Detection Matrix.

For an analytical assessment of the GenHUMS performance, the same fault definition described in section 6.4.6.2 was used again to statistically compare the results. Since the pattern match indicators are sensitive to the location of the fault present, the faults were also categorized by whether they are inner race, outer race, cage, or rolling element faults. The thresholds were set by using the statistics of the data to determine the most suitable value.

Table 14 shows the detection accuracy for each ETE CI and the pattern match energy index (EI) and detection index (DI) indicators for each PB. The highest accuracy was achieved using PB1 (1.5 to 5 kHz) and ETE_EB (98.4%). The pattern match indicators offered very good accuracy for all PBs, which may be very useful since the lower frequencies are known to be affected by vibration from other sources onboard the aircraft. For example, the pattern match EIs for PB5 (10 to 20 kHz) gave 94% accuracy compared to the 80.2% achieved using the BMS analysis. It would be recommended that if GenHUMS analysis was used, an appropriate selection of CIs be applied, since they each respond to different types of fault; and an advanced anomaly detection (AAD) process should be used to fuse all the CIs to give more intelligent alerts than a simple threshold approach.

Table 14. The GenHUMS Accuracy for Each PB and CI

CI	PB1: 1.5 to 5 kHz (%)	PB2: 15 to 20 kHz (%)	PB3: 0 to 5 kHz (%)	PB4: 5 to 10 kHz (%)	PB5: 10 to 20 kHz (%)	PB6: 20 to 40 kHz (%)
ETE_M6	75.4	71.6	76.0	64.2	74.8	70.1
ETE_MN	94.2	86.3	93.0	93.3	88.5	82.1
ETE_PP	87.9	85.9	87.5	91.1	93.3	84.2
ETE_STD	94.2	86.3	93.9	93.6	91.4	81.8
FTE_EB	98.4	86.9	94.6	92.7	90.1	77.0
FTE_TON	97.1	86.6	93.3	92.7	87.5	76.3
FTE_WHT	93.6	85.9	93.0	92.3	85.9	73.9
Pattern DI	94.3	90.7	94.4	91.8	92.3	90.5
Pattern EI	93.8	93.2	93.2	94.6	94.0	92.2

6.4.9 Comparison of External and Internal Sensor Mounting Locations.

In many installations, especially for those installed as a retrofit, the sensor may be mounted on top of the oil cooler's outside casing, recording both axial and radial vibration. The S-92 aircraft BMS sensor is fully integrated into the oil cooler and records a single vibration signal, but also records temperature. Figure 16 shows the positions of the internal BMS and an alternate externally mounted sensor. Although the analysis presented focused on the internal sensor, it would be beneficial to know whether an aircraft fitted only with a sensor mounted to the external housing could detect the fault cases as effectively and, therefore, be eligible for a CBM credit.

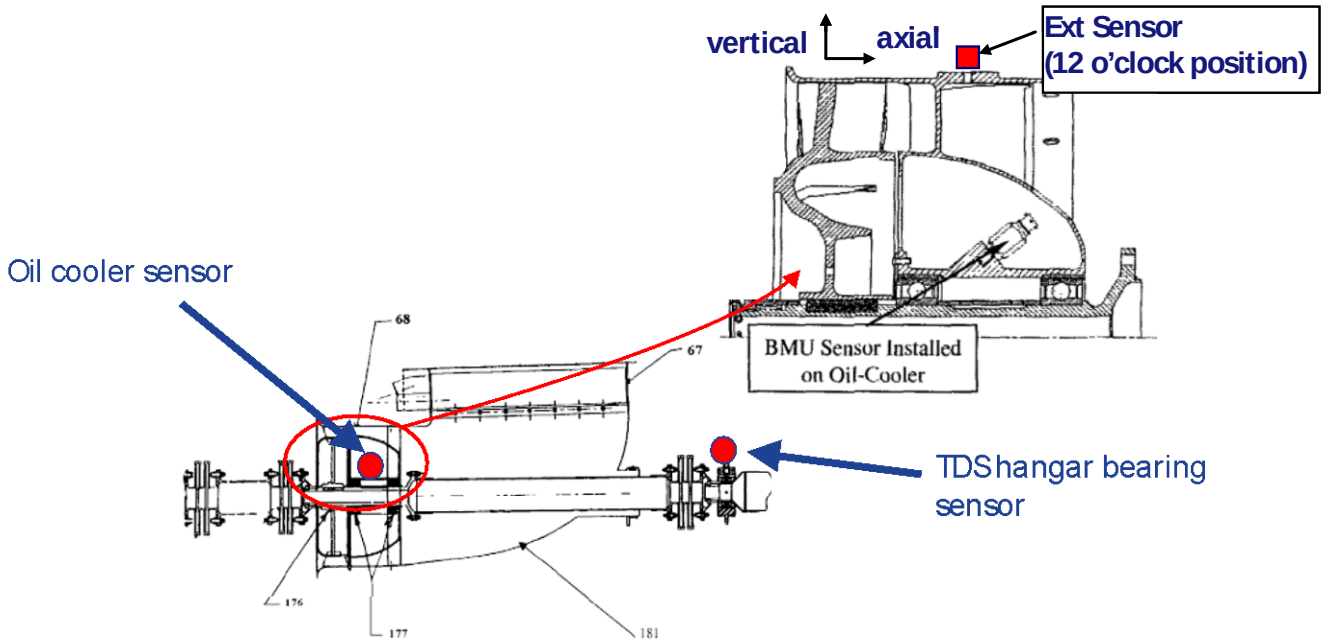


Figure 16. The S-92 Internal and External Sensor Locations

6.4.9.1 The BMS Analysis.

Figures 17 and 18 show the results of the BMS analysis applied to the external axial and radial sensor data. The broad shape of the results is very similar to the internal sensor results. However, the HP (Band 0) values are lower than the internal sensor data, and the radial LP (Band 1) values are larger (higher-frequency vibration attenuates more rapidly with distance than lower-frequency vibration). Table 15 shows the maximum and mean of the results from the LP and HP filters for the three sensors. If these sensors were used, the thresholds would have to be adjusted. Some suggested values are shown in table 15.

Table 15. Statistics of External and Internal Sensors

Statistic	PB	Internal	External Axial	External Radial
Mean	LP	0.572	0.665	1.169
	HP	0.495	0.149	0.226
Maximum	LP	3.945	2.689	4.934
	HP	2.902	0.986	1.377
Proposed Threshold	LP	1.000	0.750	1.500
	HP	0.750	0.200	0.300

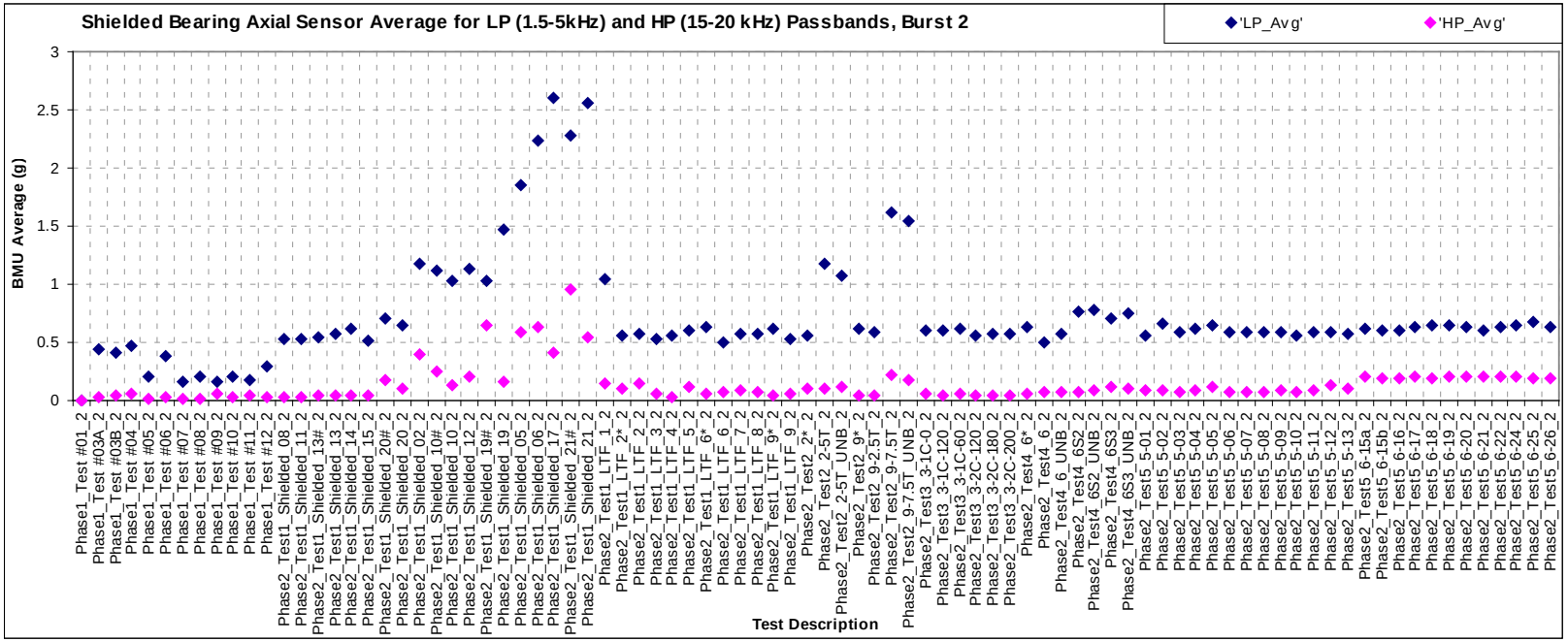


Figure 17. External Axial Sensor Averages for Burst 2 for All Phases and Tests

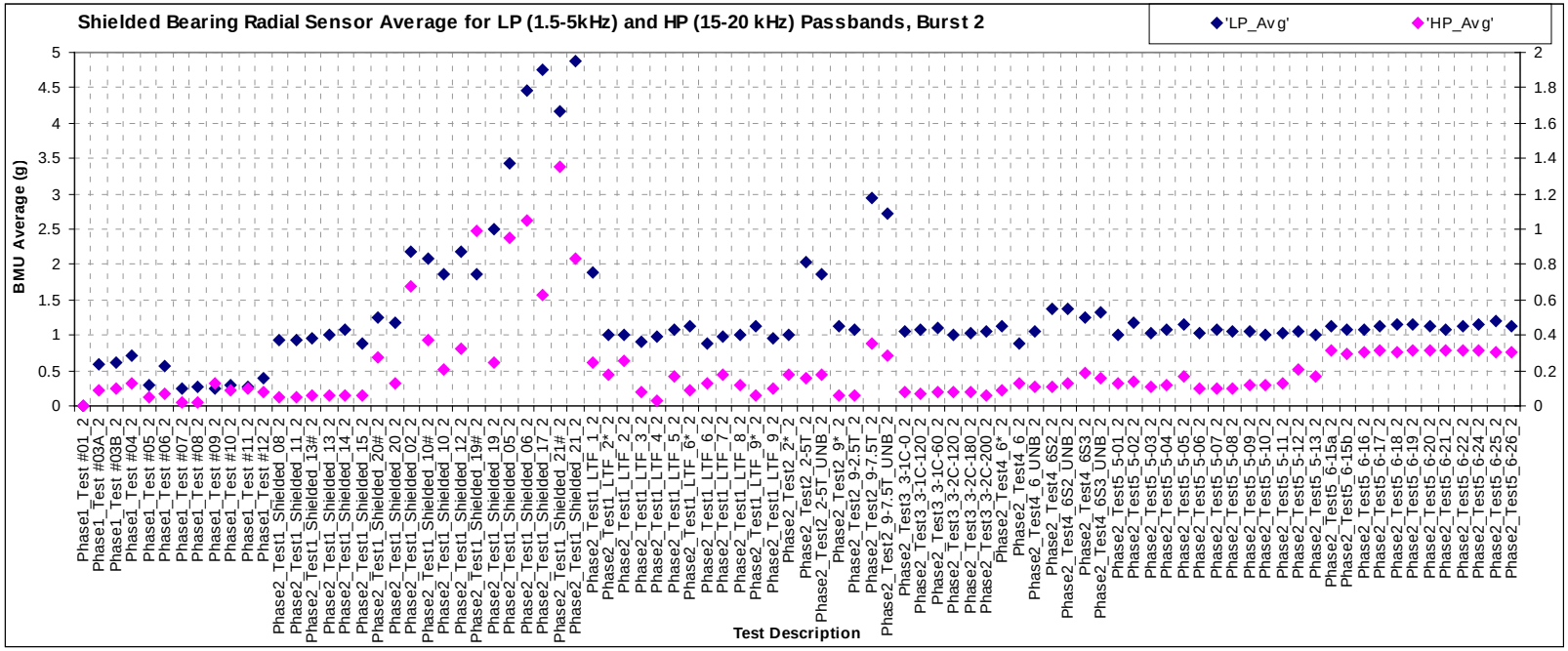


Figure 18. External Radial Sensor Averages for Burst 2 for All Phases and Tests

6.4.9.2 The GenHUMS Bearing Analysis.

The GenHUMS bearing analysis discussed in section 6.4.8 was also run using the external sensor data. Only the first burst and the BMS PBs (1.5 to 5 and 15 to 20 kHz) were used to simplify the analysis. The results show the following:

- The signal means are around 0.01 for Phase 1, but 0.2, 0, and -0.65 for Phase 2 axial, radial, and internal sensors, respectively.

- The CIs confirm that the Phase 2, test 5 LTF 6 degreased run 15a and 15b burst 1 data did not record correctly and have very low values.

- The SIG CIs are generally highest for the internal sensor and lowest for the axial sensor; however, they all seem to respond to the high-damage, shielded bearings and to the assembly-damaged bearings. Only the internal sensor rises slightly for the degreased bearing.

- FTE_EB was highest for the radial sensor; however, the results from all sensors responded to the high-damage, shielded bearings and to the assembly damaged bearings and were very slightly raised for the spalled bearing.

- The SO frequencies were much more prominent in the axial sensor data and were only present in the unbalanced runs for the radial sensor.

- The ETE_M6 CI responded to impulsive behavior in the data. In general, the internal sensor data M6 values were the highest; however, the external sensor values were highest for two tests: the shielded bearing 13 in the aft position and LTF 8 bearing tests. These are not tests for which impulsive behavior would be expected. M6 for all sensors seems to trend up for degreased runs 10 to 13.

- The other ETE CIs responded similarly to the SIG CIs except, generally the external radial sensor was highest and the internal sensor was lowest.

- The internal sensor gave the best pattern match defect indicator results. For example, the internal sensor data gave inner race DIs of around 90% for the spalled bearing (Phase 2, test 4), but the highest external sensor DI was 35%.

- The pattern match energy indices for all sensors were highest for the high-damage, shielded bearings and the assembly damaged bearings; however, in general, the BMS values were higher than those from the external sensor. As with the DIs, the BMS data gave high inner race EIs for the spalled bearing, but the UH-60 sensors did not.

In summary, most defects would have been found using the external sensor. However, this sensor was not as good as the internally mounted BMS sensor for the pattern match indicators, e.g., potentially missing the spalled bearing.

6.5 SUMMARY OF DATA ANALYSIS.

A comprehensive analysis of both S-92 oil cooler fleet HUMS data and test rig data has been performed to generate direct evidence for OCB CBM credit validation. This analysis extended beyond the required credit validation to include a wider assessment of bearing monitoring capabilities and how these could be optimized to provide the greatest CBM credit potential. The evidence that was generated provided a good basis for completing the research work into the end-to-end credit approval process in accordance with MG-15.

The following different types of analysis were performed on the acquired test rig seeded fault data.

- A comparative assessment of BMS fault detection performance using the Band 0 (15 to 20 kHz) and Band 1 (1.5 to 5 kHz) data

- An analysis to determine if BMS fault detection performance could be improved by using different frequency bands (Analyses were performed using the four octave bands of 0 to 5, 5 to 10, 10 to 20, and 20 to 40 kHz.)

- A comparison of the fault detection performance of the BMS vibration and temperature sensors

- An assessment of the additional fault detection performance that could be achieved through the application of more sophisticated signal processing to the acquired vibration data, including the use of bearing defect pattern match indicators

- An analysis of the effect of sensor location on fault detection performance, comparing the internal sensor location to an external location on top of the oil cooler fan casing

To enable the data to be compared easily, the results were averaged across all bursts for each test. The following three methods were used to summarize the response of each analysis method to each fault: (1) using heat maps, (2) using thresholds, and (3) using a summary table describing the response.

Figure 19 shows the results of applying the BMS analysis techniques to the data from the internal sensor and the external radial and axial sensors. For each sensor, the two BMS PBs were used. In addition, four octave PBs were used for the BMS sensor data. The values in the figure have been normalized by dividing all values by the mean of the values for the Phase 1 and Phase 2, test 1 LTF bearings, since these represent the most normal conditions. Normalization is necessary because the amplitudes from the different PBs can vary significantly, making it difficult to compare the response. The figure shows that all the methods responded well to the shielded bearing corrosion damage. There was a good response for all methods to the assembly damaged bearings, although the response was stronger at the lower PBs. There was a limited response to the spalled bearings, with only the lower PBs responding to the initial spall. The higher PBs gave some response to the degreased runs using the LTF 6 bearing.

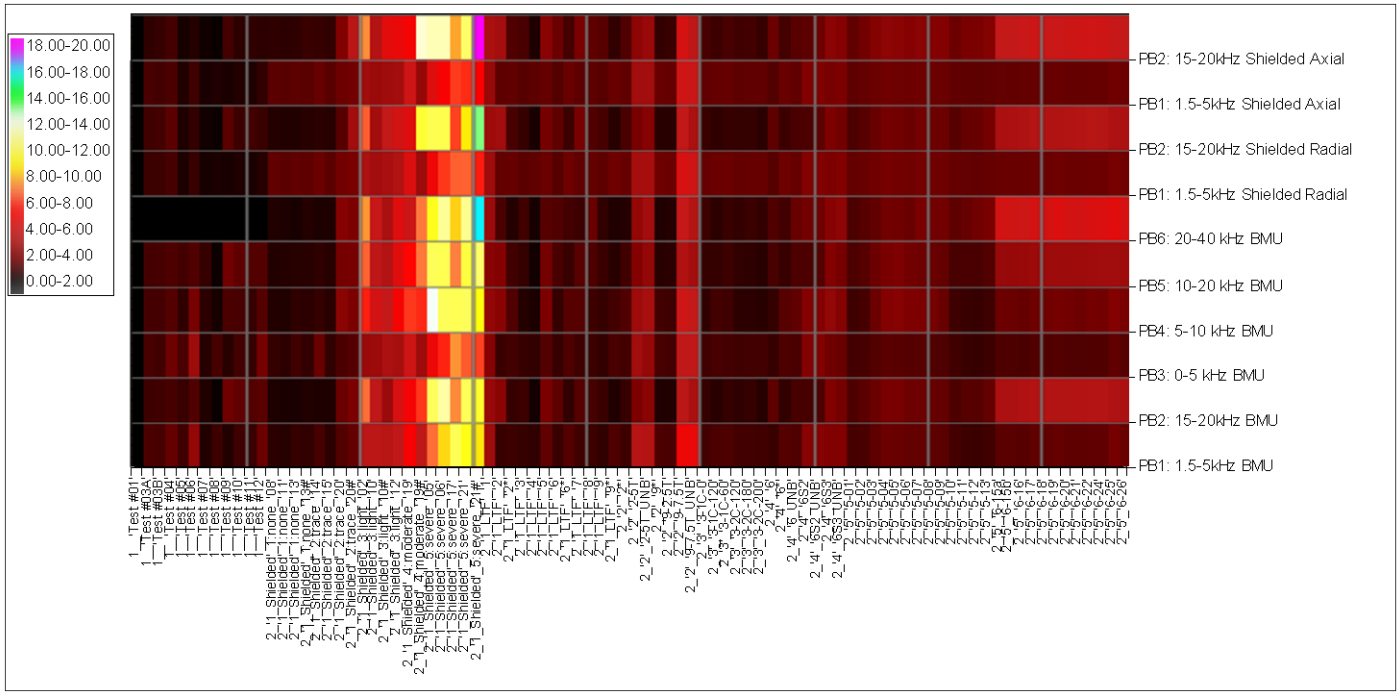


Figure 19. Response of BMS Measurements to Each Test

Figures 20 and 21 show the results of applying the GenHUMS techniques to the data from the BMS sensor. Although the four octave bands were analyzed, for simplicity, only the two BMS PBs are shown. Again, the values in the figures were normalized by dividing all values by the mean for Phase 1 and Phase 2, test 1 LTF bearings valves, since these represent the most normal conditions. Figure 21 shows the pattern match CIs and figure 20 shows the other CIs. The figures show that all the CIs responded well to the shielded bearing corrosion damage, except ETE_M6. There was a good response for all CIs to the assembly damaged bearings, although the response was stronger at the lower PBs. There was a limited response to the spalled bearings, with only the lower PBs responding to the initial spall; however, the pattern match CIs identified the inner race defect. The higher PBs gave some response to the degreased runs using the LTF 6 bearing.

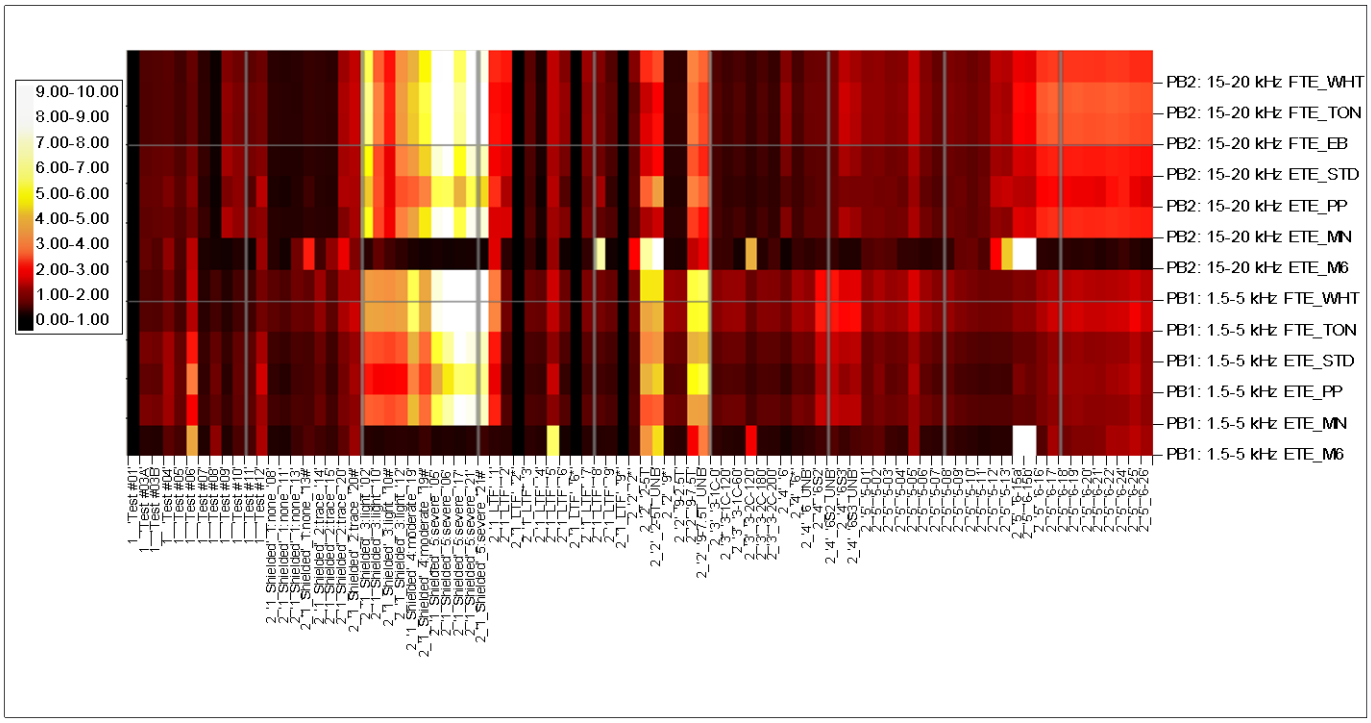


Figure 20. Response of GenHUMS CIs to Each Test

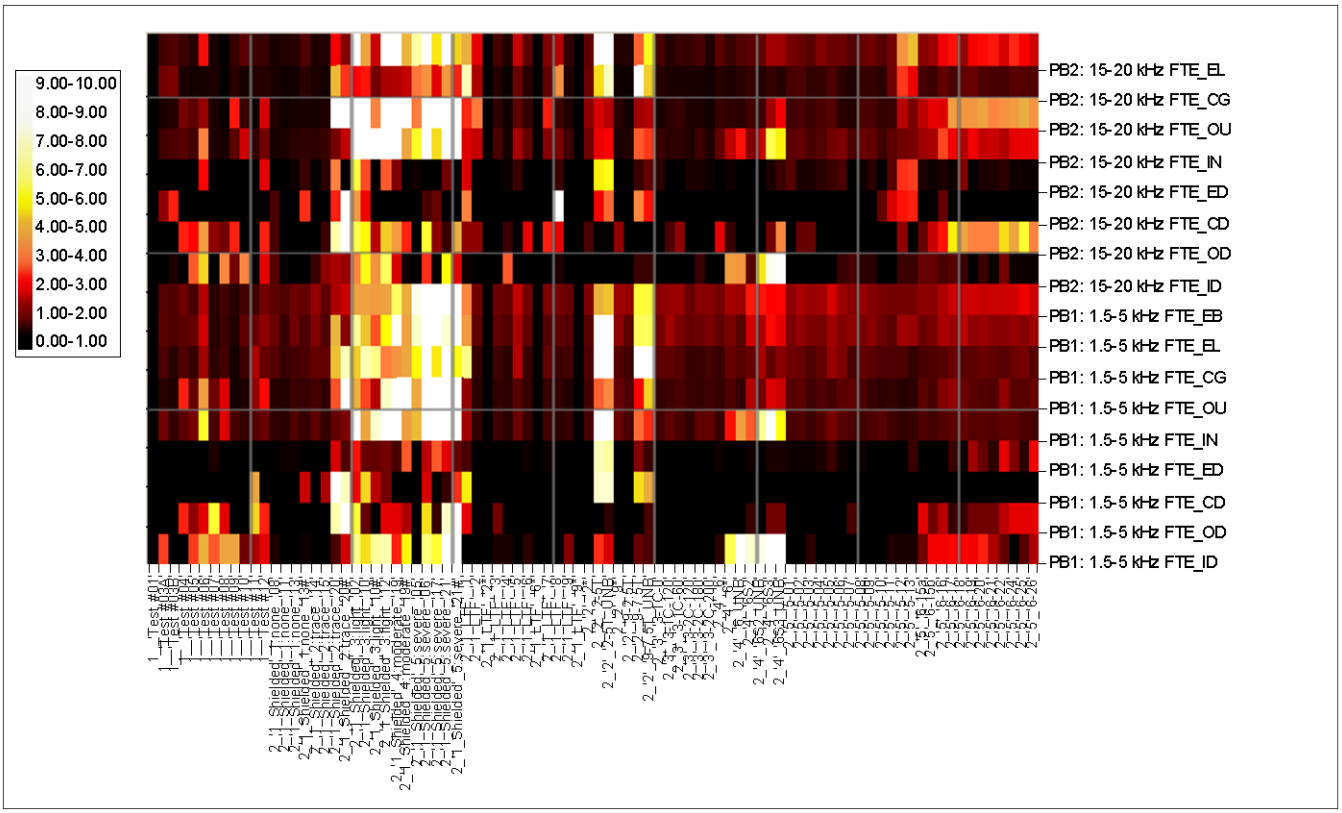


Figure 21. Response of GenHUMS Pattern Match CIs to Each Test

Tables 16 and 17 show the response of the BMS analysis to each test, and tables 18 and 19 show the response of the GenHUMS analysis. The first column gives the short name of each test. The second column indicates whether the test represented a fault condition. For the GenHUMS results, this is further split according to which bearing element has the fault. Each column then represents a different sensor and analysis PB for comparison. The tables show a value of 1 if the data are above the threshold and a 0 if it falls below the threshold. The thresholds were selected to maximize the detection capability of the analysis method. The cells are colored according to whether the result is correct. Since it is unclear whether test 5 should be considered as a fault case, it is presented in a separate table and simply colored according to whether an alert was raised (red) or not (green). The tables show that

- Phase 1, test 6, which should have normal vibration, triggered alerts on low PBs for the internal sensor and a number of GenHUMS CIs.

- Phase 2, test 1 LTF 1, which had higher vibrations due to insufficient grease, triggered alerts for all sensors, for high PBs, and for some GenHUMS CIs.

- Shielded bearings with light, medium, or severe corrosion damage were detected by all methods and sensors (except bearing 10).

- The LTF 9 bearing with 15,000 lb of simulated assembly damage was detected by all methods.

- The LTF 2 bearing with 10,000 lb of simulated assembly damage was only detected by the BMS in the lower PBs (except BMS PB5) and by the GenHUMS CIs (both PBs).

- The cracked cage test did not raise any alerts.

- The light spall on the LTF 6 bearing was only detected by the lowest PB for the internal and external axial sensors and by the GenHUMS pattern match CIs. However, trends in the results from the BMS analysis indicated that a moderate or larger spall would be detected.

- For all methods, the higher PBs respond to the LTF 6 bearing during the degreased operation.

- There were a number of false alerts for the individual GenHUMS pattern match CIs. This can be addressed by triggering alerts based on the combined pattern match detection and energy CI values.

Table 16. Detection Comparison Matrix—Internal and External Sensors, Tests 1 Through 4

Key: 1 = over threshold 0 = below threshold green = correct orange = false alarm pink = missed fault	Passband	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB3: 0-5 kHz	PB4: 5-10 kHz	PB5: 10-20 kHz	PB6: 20-40 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz
	Threshold	0.75	0.75	1.00	0.50	0.75	0.75	0.50	0.15	1.50	0.30	0.75	0.15
Test	Fault	Internal (BMS)								External Radial		External Axial	
1_Test #01	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #03A	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #03B	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #04	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #05	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #06	0	1	0	0	0	1	0	0	0	0	0	0	0
1_Test #07	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #08	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #09	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #10	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #11	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #12	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_08	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_11	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_13	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_13#	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_14	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_15	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_20	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_20#	0	0	0	0	0	0	0	0	0	0	0	0	1
2_1_Shielded_3:light_02	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_3:light_10	1	1	1	1	1	1	1	1	1	1	0	1	1
2_1_Shielded_3:light_10#	1	1	0	1	1	1	1	1	0	1	1	1	1
2_1_Shielded_3:light_12	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_4:moderate_19	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_4:moderate_19#	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_5:severe_05	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_5:severe_06	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_5:severe_17	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_5:severe_21	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_Shielded_5:severe_21#	1	1	1	1	1	1	1	1	1	1	1	1	1
2_1_LTF_1	0	1	0	1	1	1	0	1	0	1	0	1	1
2_1_LTF_2	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_2*	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_3	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_4	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_5	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_6	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_6*	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_7	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_8	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_9	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_9*	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 16. Detection Comparison Matrix—Internal and External Sensors, Tests 1 Through 4 (Continued)

Key: 1 = over threshold 0 = below threshold green = correct orange = false alarm pink = missed fault	Passband	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB3: 0-5 kHz	PB4: 5-10 kHz	PB5: 10-20 kHz	PB6: 20-40 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz
Threshold		0.75	0.75	1.00	0.50	0.75	0.75	0.50	0.15	1.50	0.30	0.75	0.15
Test	Fault	Internal (BMS)								External Radial		External Axial	
2_2_2*	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_2-5T	1	1	0	1	0	1	1	0	0	1	0	1	0
2_2_2-5T_UNB	1	1	0	1	0	1	1	1	0	1	0	1	0
2_2_9*	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_9-2.5T	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_9-7.5T	1	1	1	1	1	1	1	1	1	1	1	1	1
2_2_9-7.5T_UNB	1	1	0	1	1	1	1	1	1	1	0	1	1
2_3_3-1C-0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-1C-120	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-1C-60	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-2C-120	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-2C-180	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-2C-200	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6*	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6_UNB	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6S2	1	1	0	0	0	1	0	0	0	0	0	1	0
2_4_6S2_UNB	1	1	0	0	0	1	0	0	0	0	0	1	0
2_4_6S3	1	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6S3_UNB	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 17. Detection Comparison Matrix—Internal and External Sensors, Test 5

Key: 1 = over threshold 0 = below threshold	Passband	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB3: 0-5 kHz	PB4: 5-10 kHz	PB5: 10-20 kHz	PB6: 20-40 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz
Threshold		0.75	0.75	1.00	0.50	0.75	0.75	0.50	0.15	1.50	0.30	0.75	0.15
Test		Internal (BMS)								External Radial		External Axial	
2_'5'_'5-01'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-02'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-03'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-04'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-05'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-06'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-07'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-08'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-09'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-10'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-11'		0	0	0	0	0	0	0	0	0	0	0	0

Table 17. Detection Comparison Matrix—Internal and External Sensors, Test 5 (Continued)

Key: 1 = over threshold 0 = below threshold	Passband	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB3: 0-5 kHz	PB4: 5-10 kHz	PB5: 10-20 kHz	PB6: 20-40 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz	PB1: 1.5-5 kHz	PB2: 15-20 kHz
	Threshold	0.75	0.75	1.00	0.50	0.75	0.75	0.50	0.15	1.50	0.30	0.75	0.15
Test		Internal (BMS)								External Radial		External Axial	
2_'5'_'5-12'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'5-13'		0	0	0	0	0	0	0	0	0	0	0	0
2_'5'_'6-15a'		0	0	0	1	0	0	1	1	0	0	0	1
2_'5'_'6-15b'		0	0	0	1	0	0	1	1	0	0	0	1
2_'5'_'6-16'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-17'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-18'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-19'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-20'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-21'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-22'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-24'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-25'		0	0	0	1	0	0	1	1	0	1	0	1
2_'5'_'6-26'		0	0	0	1	0	0	1	1	0	0	0	1

Table 18. Detection Comparison Matrix—GenHUMS, Tests 1 Through 4

Key: 1 = over threshold 0 = below threshold green = correct orange = false alarm pink = missed fault	Passband					PB1: 1.5-5 kHz															PB2: 15-20 kHz														
	Threshold					0	5	50	6	40	40	40	40	0.2	0	0.2	0	0.1	0.06	0.03	10	3	40	3	40	40	40	40	0.1	0	0.1	0	0	0.03	0.02
Test	fault	IN	OU	CG	EL	ETE_M6	ETE_MN	ETE_PP	ETE_STD	FTE_ID	FTE_OD	FTE_CD	FTE_ED	FTE_IN	FTE_OU	FTE_CG	FTE_EL	FTE_EB	FTE_TON	FTE_WHT	ETE_M6	ETE_MN	ETE_PP	ETE_STD	FTE_ID	FTE_OD	FTE_CD	FTE_ED	FTE_IN	FTE_OU	FTE_CG	FTE_EL	FTE_EB	FTE_TON	FTE_WHT
1_Test #01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #03A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #03B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
1_Test #04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #06	0	0	0	0	0	1	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
1_Test #07	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #08	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #09	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
1_Test #10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #11	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1_Test #12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_1:none_13#	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_Shielded_2:trace_20	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0
2_1_Shielded_2:trace_20#	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	0	0
2_1_Shielded_3:light_02	1	1	1	0	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1
2_1_Shielded_3:light_10	1	1	0	0	0	0	1	1	1	1	0	1	0	1	0	1	0	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1
2_1_Shielded_3:light_10#	1	1	0	0	0	0	1	1	1	1	0	0	0	1	0	1	0	1	1	1	0	0	1	1	0	0	0	0	1	1	0	0	1	1	1

Table 18. Detection Comparison Matrix—GenHUMS, Tests 1 Through 4 (Continued)

Key:
1 = over threshold
0 = below threshold
green = correct
orange = false alarm
pink = missed fault

Test	fault	IN	OU	CG	EL	ETE_M6	ETE_MN	ETE_PP	ETE_STD	FTE_ID	FTE_OD	FTE_CD	FTE_ED	FTE_IN	FTE_OU	FTE_CG	FTE_EL	FTE_EB	FTE_TON	FTE_WHT	ETE_M6	ETE_MN	ETE_PP	ETE_STD	FTE_ID	FTE_OD	FTE_CD	FTE_ED	FTE_IN	FTE_OU	FTE_CG	FTE_EL	FTE_EB	FTE_TON	FTE_WHT
	Passband					PB1: 1.5-5 kHz															PB2: 15-20 kHz														
	Threshold					0	5	50	6	40	40	40	40	2	0	2	0	1	06	02	00	3	40	3	40	40	40	40	1	0	1	0	0	03	02
2_1_Shielded_3:light_12	1	1	1	0	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1
2_1_Shielded_4:moderate_19	1	1	0	0	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1
2_1_Shielded_4:moderate_19#	1	1	0	0	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1
2_1_Shielded_5:severe_05	1	0	0	0	0	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1
2_1_Shielded_5:severe_06	1	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	1
2_1_Shielded_5:severe_17	1	1	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1	1
2_1_Shielded_5:severe_21	1	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	1	1	1	1	1	1	1
2_1_Shielded_5:severe_21#	1	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	1
2_1_LTF_1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	0	0	1	1	0	0	0	0	0	1	1	1	1	1	1
2_1_LTF_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1
2_1_LTF_2*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_6*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
2_1_LTF_8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0
2_1_LTF_9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_1_LTF_9*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_2*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_2-5T	1	1	0	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	1	1	0	1	1	0	0	0	1	0	0	1	1	1	0	1
2_2_2-5T_UNB	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	1	0	0	1	1	1	1	1
2_2_9*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_9-2.5T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_2_9-7.5T	1	0	0	1	0	1	1	1	1	0	0	1	0	0	0	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	1	0	1	1	1
2_2_9-7.5T_UNB	1	0	0	1	0	1	1	1	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1
2_3_3-1C-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-1C-120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-1C-60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-2C-120	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-2C-180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_3_3-2C-200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6*	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6_UNB	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6S2	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_4_6S2_UNB	1	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2_4_6S3	1	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0
2_4_6S3_UNB	1	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0

Table 19. Detection Comparison Matrix—GenHUMS, Test 5

Test	PB1: 1.5-5 kHz															PB2: 15-20 kHz														
	500	5	50	6	40	40	40	40	0.2	0	0.2	0	0.1	0.06	0.02	1000	3	40	3	40	40	40	40	0.1	0	0.1	0	0	0.03	0.02
	ETE_M6	ETE_MN	ETE_PP	ETE_STD	FTE_ID	FTE_OD	FTE_CD	FTE_ED	FTE_IN	FTE_OU	FTE_CG	FTE_EL	FTE_EB	FTE_TON	FTE_WHT	ETE_M6	ETE_MN	ETE_PP	ETE_STD	FTE_ID	FTE_OD	FTE_CD	FTE_ED	FTE_IN	FTE_OU	FTE_CG	FTE_EL	FTE_EB	FTE_TON	FTE_WHT
2_5_5-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2_5_5-12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0
2_5_5-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0
2_5_6-15a	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	0
2_5_6-15b	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	1	1	0
2_5_6-16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1	1
2_5_6-17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1
2_5_6-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1
2_5_6-19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	1	1	1
2_5_6-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	1	1	1
2_5_6-21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	0	1	1	1
2_5_6-22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1
2_5_6-24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1
2_5_6-25	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	1	0	0	0	1	0	0	1	1	1
2_5_6-26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	1	1

Table 20 shows the detailed response and gives a summary of the fault detection capability of each test method.

Table 20. Summary Response Descriptions of Each Method and PB to the Faults

Method	Passband	Phase 1 and Phase 2 LTF	Phase 2, Test 1-Corrosion	Phase 2, Test 2-Assembly Damage	Phase 2, Test 3-Cage Crack	Phase 2, Test 4-Spall	Phase 2, Test 5-Degreased	Overall Observations
S-92 BMS Current PBs	PB1: 1.5-5 kHz	Mostly low levels: average 0.4 g. Except: Phase 2 LTF 1 maximum 1.07 g and Phase 1, test 6 maximum 0.91 g.	Light and above raised in proportion to damage. All above 1.2 g	Raised in proportion to damage, easily detected. 10 klb ->1.2 g, 15 klb ->1.8 g	No response. Average 0.38 g	Raised for both trace and light spall. Minimum 0.7 g, average 0.74 g.	No response. Average 0.5 g	With threshold of 0.75, would detect corrosion, assembly damage, and spall, but fleet data indicates low PB not repeatable for component health, and this threshold would produce unacceptable quantity of false alerts in the field.
	PB2: 15-20 kHz	Mostly low levels: average 0.2 g, maximum 0.59 g (Phase 2, LTF 1 degreased)	Light and above raised in proportion to damage, except bearing 10	Raised in proportion to damage.10 klb damage ->0.4 g, 15 klb ->0.7 g	No response. Average 0.15 g	Relative to threshold only slightly raised for light spall (maximum 0.42 g). Increasing trend from trace to light spall to degreased.	Raised to average of 0.7 for LTF 6 (degreased light spall)	Current threshold of 0.75 detects corrosion and 15-klb assembly damage. Light spalls and degreased bearing not detected, but trend indicates moderate to severe would be detected.
S-92 BMS Temperature	N/A							No response to magnitude of any faults tested.
BMS Additional PBs	PB3: 0-5 kHz							Similar to PB1
	PB4: 5-10 kHz	Mostly low levels: average 0.32 g, maximum 0.72 g (Phase 2, LTF 1)	Light and above raised in proportion to damage. All above 1 g. Bearing 20 also slightly raised.	Raised in proportion to damage, easily detected. 10 klb ->0.8 g, 15 klb ->1.2 g	No response. Average 0.23 g	Slightly raised for both trace and light spall. Minimum 0.6 g, average 0.63 g.	Slightly raised for LTF 6, and LTF 5 runs 3-9, but maximum is only 0.6.	Increased sensitivity to assembly damage relative to PB2, but no trend for spall damage.
	PB5: 10-20 kHz	Mostly low levels: average 0.26 g, maximum 0.5 g (Phase 2, LTF 1)	Light and above raised in proportion to damage. All above 0.8 g.	Raised in proportion to damage. 10 klb ->0.5 g, 15 klb ->0.7 g	No response. Average 0.18 g	Slightly raised for light spall. Maximum 0.49 g.	Raised to average of 0.65 g for LTF 6	Equivalent detection to PB2
	PB6: 20-40 kHz	Not applied to Phase 1. Phase 2 LTF mostly low levels: average 0.05 g, maximum 0.13 g (Phase 2, LTF 1)	Light and above raised. Bearings 10, 12, and 19 lower than expected.	Raised in proportion to damage. 10 klb ->0.13 g, 15 klb ->0.17 g	No response. Average 0.04 g	Almost no response	Raised to average of 0.21 g for LTF 6	Requires higher-frequency acquisition. Almost no response to spall. Less good response for corroded bearings than other methods.

Table 20. Summary Response Descriptions of Each Method and PB to the Faults (Continued)

Method	Passband	Phase 1 and Phase 2 LTF	Phase 2, Test 1-Corrosion	Phase 2, Test 2-Assembly Damage	Phase 2, Test 3-Cage Crack	Phase 2, Test 4-Spall	Phase 2, Test 5-Degreased	Overall Observations
External Radial Location	PB1: 1.5-5 kHz	Phase 1 average: 0.38 g, Phase 2 LTF average: 1.08 g. maximum 1.8 g (Phase 2, LTF 1)	Light and above raised in proportion to damage. All above 1.8 g	Raised in proportion to damage. 10 klb ->2 g, 15 klb ->2.9 g	No response. Average 1.05 g	Very little response, average 1.3 g	No response. Average 1.09 g	Low PB not repeatable for component health.
	PB2: 15-20 kHz	Phase 1 average: 0.07 g, Phase 2 LTF average: 0.13 g. maximum 0.27 g (Phase 2, LTF 2)	Light and above raised. Bearings 10, 12, and 19 lower than expected. All but 10 above 0.3 g	Slightly raised for most sever damage. 10 klb ->0.18 g, 15 klb ->0.32 g	No response. Average 0.07 g	No response, average 0.14 g	Raised to average of 0.31 g for LTF 6	Magnitudes reduced by factor of 2 relative to S-92 BMS location. Separation from healthy to faulted not as clear. Spall would need to be more severe before detection. With reduced thresholds detection is possible with higher false alerts expected.
External Axial Location	PB1: 1.5-5 kHz	Phase 1 average: 0.26 g, Phase 2 LTF average: 0.6. maximum 1.04 g (Phase 2, LTF 1)	Light and above raised. Bearing 19 lower than expected. All above 1 g	Significantly raised in proportion to damage. 10 klb ->1.15 g, 15 klb ->1.6 g	No response. Average 0.56 g	Very little response, average 0.71 g	No response. Average 0.56 g	Low PB not repeatable for component health.
	PB2: 15-20 kHz	Phase 1 average: 0.03 g, Phase 2 LTF average: 0.08. maximum 0.15 g (Phase 2, LTF 2)	Light and above raised. Bearings 10, 12, and 19 lower than expected. All but 10 above 0.24 g	Slightly raised in proportion to damage. 10 klb ->0.12 g, 15 klb ->0.2 g	No response. Average 0.05 g	Slightly raised for final spall. Maximum 0.11 g.	Raised to average of 0.2 g for LTF 6	Magnitudes reduced by a factor of 3, relative to S-92 BMS location. Separation from healthy to faulted was not as clear. Spall would need to be more severe before detection. With reduced thresholds, detection is possible with higher false alarms expected.

Table 20. Summary Response Descriptions of Each Method and PB to the Faults (Continued)

Method	Passband	Phase 1 and Phase 2 LTF	Phase 2, Test 1-Corrosion	Phase 2, Test 2-Assembly Damage	Phase 2, Test 3-Cage Crack	Phase 2, Test 4-Spall	Phase 2, Test 5-Degreased	Overall Observations
GenHUMS	PB1: 1.5-5 kHz	Across most CIs, values are low. Phase 1 test 6 and Phase 2 LTF 1 have generally higher values. OD high for 1 burst for Phase 1, tests 7 and 11.	Light and above clearly picked up by most CIs. Pattern match clearly identifies fault except for bearings 5 and 19. Also high CD and OD for bearing 20.	Most CIs clearly raised. Pattern match clearly identifies ED for 10 klb and CD for 10 and 15 klb	All low, except one high M6 value	Good detection by inner race pattern match. Also slightly raised for EB and TON	Not raised for any CI	Low PB not repeatable for component health.
	PB2: 15-20 kHz	Across most CIs, values are low. Phase 1, test 6 has a few high pattern match scores.	Light and above clearly picked up by most CIs. Pattern match clearly identifies fault except for bearings 5 and 19. Also high CD and OD for bearing 20	Most CIs raised. Pattern match less clear than PB1	All low	Good detection by inner race pattern match.	Not raised for any CI	Good spall detection at trace and light levels using high PB pattern match indicators. Need to compliment with BMS-like (bearing energy) processing to quantify size relative to type of spall. Potential for false alerts across fleet would have to be managed with threshold policy and down selection of CIs.

EB = FTE_EB = energy of the band-passed envelope spectrum
TON = FTE_TON = tonal energy of the band-passed envelope spectrum
ED = FTE_ED = detection index for tone pattern generated by rolling element damage
CD = FTE_CD = detection index for tone pattern generated by cage damage
OD = FTE_OD = detection index for tone pattern generated by outer race damage

Based on the comprehensive analysis described in this section, the following specific conclusions can be drawn from the rig test results.

- The rig test data can be directly compared to the flight data in terms of signal magnitude and frequency content. Some features were present in the rig test data that are related to the rig rather than the bearing, but these had no significant effect on the analysis and could be ignored.

- Applying the BMS analysis to the BMS sensor Band 1 (1.5- to 5-kHz) data, the significant rig test faults (bearing corrosion damage, assembly damage, and light spalling) could be detected, while all other data did not generate alerts. However, analysis of the fleet data has shown that this PB can be affected by other nearby vibration sources; therefore, its primary use is for a sensor health check.

- Applying the BMS analysis to the BMS sensor Band 0 (15- to 20-kHz) data gives good detection of the bearing corrosion damage and the highest level of assembly damage. Measurements also responded to the lower levels of assembly damage, light spalling, and the degreased run, but not sufficient enough to raise an alert using the current aircraft threshold of 0.75, which was set from a safety-of-flight perspective. However, the results indicate that if the faults were to become more severe, the data would respond and trigger alerts. This threshold has been validated by in-service experience, with no bearing faults being missed and no unacceptable false alert rate problems being encountered. A bearing manufacturing problem, with some bearing and seal damage that occurred during assembly and packing, was successfully detected and corrected. The rig test evidence has also shown that the BMS is capable of detecting bearing raceway corrosion and degradation and dents resulting from simulated assembly damage. Although the light spalling was not detected, spalling was a progressive failure mode, and there was both some test rig evidence and evidence from other vibration monitoring experience that the BMS detected more significant spalling. It was not possible to show that the BMS could detect a cracked bearing cage or a lack of grease in the bearing, although increased levels were recorded for the degreased test. However, neither of these conditions affected the operation of the bearing during the test.

- Using other PBs (such as 5 to 10 or 10 to 20 kHz) did not significantly improve the fault detection performance.

- As expected, the BMS temperature sensor did not respond in any of the tests undertaken. The BMS was designed to use vibration monitoring to provide early fault indications and temperature monitoring to provide cockpit indications when real-time crew action is required during late stages of failure progression.

- An alternate external sensor location gave similar, but slightly worse, detection capability compared to the internal BMS sensor; however, it responded to the same faults and so should be eligible for CBM credits.

- The more advanced GenHUMS analysis offers additional fault detection capability by using the bearing defect pattern-matching techniques. It allows the fault source to be more accurately determined and is able to better identify spalling damage than other methods. However, this would be a more complex and expensive method to implement and would need to be matured to ensure that it did not cause unacceptable false alerts.

The primary objective of the analysis was to assess the potential of the BMS approach to provide CBM credits on the S-92 OCBs in addition to fulfilling its design purpose of providing enhanced safety of flight monitoring. The test results indicated that the BMS Band 0 (15- to 20-kHz) data, with a monitoring threshold of 0.75 g, would detect a range of bearing faults before they reached critical condition and, therefore, can be used for CBM. The BMS Band 1 (1.5- to 5-kHz) data cannot be used directly to provide CBM credit on the S-92 OCBs, but satisfies its design purpose of monitoring sensor health. The temperature monitoring performed by the BMS is primarily a flight safety function and is not considered suitable for providing CBM credit. It does, however, allow the criticality to be classified as Major, as opposed to a higher criticality, because it provides a last line of defense against imminent failure.

Although rig tests generated fault data that normally could not be obtained on the aircraft, it still has limitations. It is always difficult to propagate faults under rig test conditions, and this is particularly true for relatively lightly loaded oil cooler fan bearings. Therefore, the amount of direct evidence that can be gathered for CBM credit validation will always be limited; this highlights the importance of being able to effectively combine direct and indirect evidence when assessing CBM credit potential. However, the rig tests have also provided evidence on the relative significance of different bearing conditions, showing that the S-92 OCBs can satisfactorily operate for long periods with a cracked cage or no lubrication.

7. THE TBO EXTENSIONS FOR S-92 AND UH-60 OIL COOLERS.

7.1 THE HUMS DEVELOPMENT AND CERTIFICATION METHODOLOGY FOR THE S-92 AIRCRAFT.

The development and certification of a HUMS for the S-92 aircraft would ultimately enable HUMS-based maintenance credits in compliance with MG-15. A key decision, based on a critical review of MG-15, was to invest in the upgrade and certification of onboard software to Level B, according to DO-178B [3]. In 2003, SAC presented a plan [4] for FAA certification of HUMS for the S-92 aircraft, in accordance with the MG-15. As a follow up, SAC later completed an S-92A HUMS certification test plan [5].

In reference 4, it was noted that

> "…in the certification of the Goodrich HUMS on the S-92 aircraft, the "end-to-end" process is from the aircraft sensors to the multi-function-displays (MFD's) on the aircraft, as well as data written onto the onboard card by the onboard Data Transfer Unit (DTU). …All HUMS functional calculations and data manipulation of the sensor data will be performed by the airborne unit only. All maintenance credits sought in this document are also based on the airborne HUMS".

The ground station system (GSS), considered a commercial off-the-shelf (COTS) tool, is used only to view, trend, plot, and archive the data. The GSS data can be used by the operator to support maintenance decisions, but it is "not necessary for the maintenance activities/credits since maintenance related information is displayed on the MFD's" [4]. Therefore, the proposed certification process focused on the onboard software and MFD data, not the GSS software and data. Reference 4 consists of 11 sections, including HUMS System Overview, Credit Validation, Compliance Check List and Method of Compliance, Functional Hazard Analysis, and Configuration Determination. The Credit Validation section covered several optional credits, including the following: operational usage, regime data, flight manual exceedance, gearbox maintenance, engine vibration, and drive train. For each credit mentioned above, the following information was provided: functional description, validation methodology, CIS, continued airworthiness, and ground station verification.

7.2 THE S-92 OCB CBM CREDIT.

The FAA research program focuses on the validation requirements for obtaining a CBM credit on the S-92 OCB in accordance with MG-15, which covers the following areas.

- Description of application and associated credit
- Understanding of the physics involved
- Validation methodology
- Introduction to service
- Continued airworthiness (synthesis)

This report describes the process to define the credit as the extension or elimination of the OCB TBO, which is driven by the bearing replacement time and the bearing failure modes that need to be detected. A credit validation plan has also been developed, including an OCB rig test plan to generate additional evidence for credit validation. An extensive analysis of the rig test data was performed, which demonstrated that the BMS can reliably detect OCB faults, and therefore has the potential to provide the desired CBM credit. A credit application could be made in accordance with MG-15, and examples of the required supporting plans for introduction to service and continued airworthiness have been generated.

During the FAA research program, the OCB TBO was extended (by SAC, independently from the subject project) from 2500 to 3500 hours using the traditional LTF-based approach. As an additional input to the research, the following sections describe the process that was used by SAC to obtain the TBO extension and compare it to the requirements of MG-15. There is considerable synergy between the LTF-based approach that is defined in MG-15, and the process used during this research would satisfy most of the key requirements in MG-15.

7.3 THE S-92 OIL COOLER TBO EXTENSION.

This section provides a brief summary of efforts to extend the original TBO for the internal bearing of the oil cooler installed on the S-92 aircraft using traditional TBO extension methods. The OCB TBO is covered under Chapter 5 of the S-92 Aircraft Maintenance Manual (AMM)

[6]. The AMM has two chapters that provide the Airworthiness Limitations (AWL) and Inspection Requirements for the S-92. Chapter 4 contains the mandatory requirements of the FAA-Approved Limitations and Replacement Schedule. Chapter 5 contains the Time Limits and the Scheduled Maintenance Checks that are recommended by SAC and do not require FAA approval. The OCB TBO is covered in the supplementary replacement schedule that is contained within Chapter 5. The supplementary replacement schedule lists items that are recommended to be replaced at a specified interval and are not listed in Chapter 4. Under a LTF program for the S-92, SAC recognized and pursued the opportunity to extend the OCB TBO using traditional SAC methods that resulted in an update to Chapter 5 of the AWL portion of the AMM.

The S-92 LTF-based OCB TBO expansion approach is described herein because it serves as a traditional baseline approach for comparison to MG-15 requirements. The subject research focused on an example OCB TBO extension and elimination credits partly because of the availability of the baseline approach for comparison when showing how to achieve a HUMS-based OCB TBO credit that is compliant with MG-15. It should be emphasized that SAC did not formally apply for a HUMS-based credit for the S-92 OCB TBO update. A HUMS-based credit was not required because the HUMS played a support role in the SAC process to substantiate the TBO adjustment. However, the analysis of the approach taken shows the parallels between the SAC LTF TBO expansion project and the MG-15 requirements. This comparison allows for the conclusion that the SAC LTF-based substantiation approach would be compliant with MG-15 requirements if it was formalized as a HUMS-based CBM credit. The details of the comparison are provided in sections 4.4, 7.3.1, and 7.3.2, respectively, with a focus on the latter two of the following three high-level MG-15 requirements [1]:

- Equipment Installation/Qualification (both airborne and ground)
- Credit Definition and Validation Activities
- ICA and CIS Activities

7.3.1 Credit Definition and Validation Activities.

Elements of SAC's LTF-based OCB TBO adjustment effort map well to MG-15 credit validation requirements. As indicated in figure 22 and table 21, the definition of credit validation requirements must be based on a solid understanding of the physics of failure, as detailed in section 5.1.

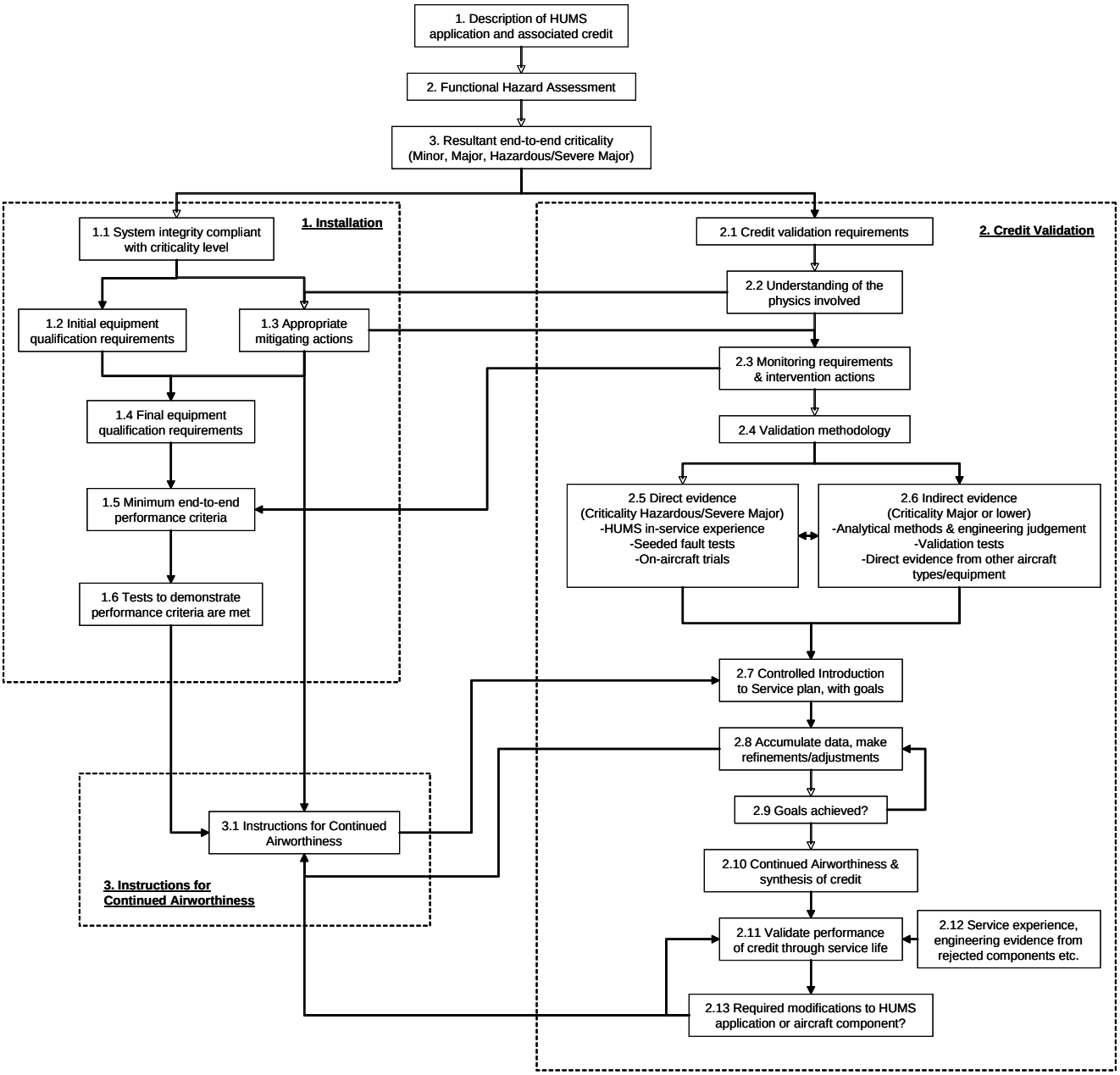


Figure 22. Flow Chart for Certifying a CBM Credit in Accordance With MG-15

Table 21. Comparison of MG-15 Requirements to SAC LTF-Based OCB TBO Extension

AC 29-2C MG-15 Requirements	SAC LTF-Based OCB TBO Update
Credit Definition	
1. Description of HUMS application and associated credit	Defined within a subset of S-92 LTF objectives
2. Failure Hazard Assessment	OCB FMEA
3. Resultant end-to-end criticality (Minor, Major, and Hazardous/Severe Major)	Class III (Major) criticality established in the OCB FMEA
Credit Validation and Performance Verification	
2.1 Credit validation requirements	S-92 LTF Plan
2.2 Understanding the physics involved	OCB FMEA
1.3 Appropriate mitigating actions	Retain periodic inspections
2.3 Monitoring requirements and intervention actions	HUMS/BMS monitoring viewed as one of three compensating provisions inherent to the design and prescribed maintenance program
1.5 Minimum end-to-end performance criteria	HUMS/BMS probability of detection
2.4 Validation methodology	S-92 LTF plan
2.5 Direct evidence (Criticality Hazardous/Severe Major)	Seeded faults test plan and fleet R&M/HUMS data analysis, including both visual and teardown inspection
2.6 Indirect evidence (Criticality Major or lower)	S-92 LTF plan used direct evidence despite OCB failure Class III (Major)
1.6 Tests to demonstrate performance criteria are met	Seeded faults test plan and fleet R&M/HUMS data analysis, including both visual and teardown inspection
ICA and CIS	
2.7 Controlled Introduction to Service plan, with goals	S-92 LTF Plan
3.1 Instructions for Continued Airworthiness	Updated AMM and HUMS manuals, including updated AWL OCB TBO and continued periodic inspections
2.8 Accumulate data, make refinements and adjustments	S-92 LTF plan execution. Continued gathering and analysis of direct physical evidence. FRACAS tracking and reporting.
2.9 Goals achieved	Yes
In-Service Experience	
2.10 Continued airworthiness and synthesis of credit	Updated AMM and HUMS manuals, including updated AWL OCB TBO and continued periodic inspections
2.11 Validate performance of credit through service life	FRACAS tracking and reporting
2.13 Service experience, engineering evidence from rejected components, etc.	FRACAS tracking and reporting
2.13 Required modifications to HUMS application or aircraft component, or opportunities for credit development	FRACAS tracking and reporting

FRACAS = Failure Reporting, Analysis, and Corrective Action System

The first progression, which would eventually result in excessive vibration, has a Class IV (Minor) failure mode because it does not have significant impact on primary OCB functionality. The second progression has a Class III (Major) failure mode, because compensating provisions

result in end effects that are detectable long before conditions become hazardous. It is important to note that the OCB design and TBO criticality is based on multiple compensating provisions, which supports HUMS/BMS.

MG-15 states that "This range of applications will have a corresponding range of criticality for the systems from No Effect to Hazardous/Severe-Major" [1]. Therefore, the S-92 OCB TBO is a suitable example credit for demonstrating the TBO extension based on direct and indirect evidence coupled with HUMS system application.

Direct evidence gathered under the LTF program substantiated that an OCB TBO credit was possible based on the inspections performed during an overhaul and other occasions indicating the bearings were in good condition and could continue in service for a significantly longer time than the original TBO. The SAC LTF objectives for the OCB effort were to uncover premature component wear as the TBO was incrementally increased; to revise the TBOs, as appropriate; and to recommend design changes, if necessary. The S-92 OCB TBO extension substantiation was mainly achieved by gathering direct evidence rather than indirect evidence as allowed by MG-15 for Class III (Major) criticality. The direct evidence included fleet R&M data, component inspections, depot-level teardown analyses, and limited seeded fault tests to better understand failure progression rates. The S-92 LTF program was supported by an extensive application of SAC's Failure Reporting, Analysis, and Corrective Action System (FRACAS). The S-92 FRACAS was developed to track and report failures occurring in tests and while in service, providing a closed-loop system in which all failures are considered and closed. FRACAS reports cannot be closed until repairs and design changes are evaluated for effectiveness and effectivity by validating that the original failure mode was resolved and no other failure modes resulted.

There were two critical decision-making elements for the S-92 OCB TBO extension. First, the inspections should not reveal any defects with significant impacts on the OCB functionality within the new TBO period. Second, the HUMS system should be able to detect OCB defects and degradation of relevance. Two levels of LTF inspections were performed, including healthy units prior to TBO, units that were removed per TBO, and units removed due to excessive vibration indications from the HUMS/BMS. The first-level visual inspections were routinely conducted at the aircraft without oil cooler or OCB disassembly. Because the OCB is embedded within the fan assembly, at-aircraft visual inspections primarily looked for signs of excessive play in the drive shaft and purged grease around the fan entrance and exit. An excessive amount of purged grease can be a sign of seal damage, overheating, or grease degradation. Numerous visual OCB inspections were also conducted at the depot level, looking for signs of roughness, excess play, etc. Finally, numerous second-level teardown analyses were also performed. All the OCB teardown analyses indicated normal wear, such as mating blower liner wear and fretting between the bearing outer race and the liner, which have no adverse effect on OCB performance.

All S-92 LTF OCB inspections indicated that the OCBs were in good condition when the inspections were performed. The overall condition of the grease and bearings was good, and the normal wear found in the bearings had no adverse effect on bearing performance. HUMS was confirmed to detect OCB faults long before bearing performance was compromised.

Finally, seeded fault tests were also performed to better understand the defect progression rates, which verified a very slow defect progression for the lightly loaded OCB. For instance, SAC conducted an instrumented bearing dry-run test (no bearing grease and with two seeded cage defects) for 150 hours, resulting in no visible defect progression.

The direct evidence substantiated that the OCB TBO could be extended and the OCB could safely remain in service long after fault detection by the HUMS/BMS. While SAC's approach to OCB TBO adjustment did not depend solely on HUMS/BMS monitoring, SAC's S-92 LTF experience has proven that the HUMS and BMS vibration monitoring has a high probability of detecting early-stage effects, supported by OCB temperature monitoring of late-stage failure effects and periodic inspection.

7.3.2 Instructions for Continued Airworthiness and Controlled Introduction to Service Activities.

As a result of this validation process, the S-92 dynamics Integrated Product Team recommended an increase in the TBO from 2500 to 3500 hours. MG-15 requires development of both ICA and CIS plan for each HUMS-based CBM credit to be approved. This should include a clear definition of the criteria for successful completion of the CIS phase. For the SAC LTF-based OCB TBO extension, engineering instructions were incorporated into updates to the AMM, AWL, and HUMS manuals. Continuous airworthiness is guaranteed through the continued use of periodic inspections and HUMS and BMS OCB vibration and temperature monitoring. After each flight, vibration level-1 or -2 exceedances are reported to the pilot via check BMS indications in the cockpit MFD report. The aircraft can continue to fly for 25 hours after a vibration level-1 exceedance. A vibration level-2 exceedance causes the aircraft to be grounded until appropriate maintenance actions are taken. HUMS and BMS criteria are periodically updated to improve the performance (reducing false alarms). Periodic visual oil cooler inspections also are performed to make sure the bearings are working properly. If excessive shaft play or purged grease is found during visual inspection, the oil cooler is removed and a teardown inspection is performed to further validate HUMS/BMS performance. The TBO increase was further validated via evaluations of early high-time bearings reaching 3000 and 3500 hours. Service experience continues to be monitored via the S-92 FRACAS initiative. The HUMS and BMS performance and the HUMS and maintenance manuals are periodically reviewed to determine the need for further improvements.

7.3.3 Comparison of SAC Procedure for OCB TBO Extension With the MG-15 Requirements.

The TBO of the S-92 oil cooler was extended from 2500 to 3500 hours through the LTF-based process described above. A similar approach could be applied to further extend and potentially remove the TBO. This baseline process was analyzed and compared to MG-15 requirements to show similarities and gaps. The following is quoted from the MG-15 requirements:

> "**Credit Validation**. HUMS applications for which credits are sought must be validated. For each application, evidence shall be provided that the physics involved is understood and therefore that the monitoring technique/algorithm/parameter, rejection criteria, and associated intervention

actions are well chosen. The designer of the component/equipment to be monitored is the most logical choice for this determination.

However, in some cases the source can be from any organization as long as the validation criteria herein can be satisfied. If changes are proposed to an approved system, re-evaluation is required to ensure existing credit(s) are not invalidated. The degree of effort will vary and depend on the application type, the credit sought, and the consequences of failure or any other malfunction. The validation process would generally need to include the following:

1) Description of application and associated credit.
2) Understanding of the physics involved.
3) Validation methodology.
4) Introduction to service.
5) Continued airworthiness (synthesis)." [1]

The above MG-15 requirements are addressed by the SAC LTF-based efforts as follows:

1. LTF OCB TBO extension objectives

2. OCB FMEA would yield a Class III (Major) hazard criticality

3. LTF plan to gather and analyze direct evidence (as described in detail above, although MG-15 requires only indirect evidence for Class III criticality), establish new TBO, and validate new TBO through gathering and analysis of additional direct evidence.

4. Updates to AMM and AWL manuals

5. LTF plan to continue gathering and analyzing HUMS and BMS and direct evidence at incremental hours up to the new TBO. Continued FRACA tracking and reporting, which is an inherent part of the S-92 program continuous improvement initiatives.

These high-level MG-15 requirements were analyzed in detail throughout this research effort as summarized in figure 22 and table 21. Table 21 provides a more detailed comparison of the SAC LTF approach with MG-15 requirements. The left column provides MG-15 requirements using the same structure as table 21. The right column maps elements of the LTF approach to MG-15 requirements. The LTF elements details are provided in sections 4-6. Despite that the SAC's LTF approach was not based solely on a HUMS-enabled credit or the application of MG-15, the detailed elements of the approach map well to MG-15 requirements. A formal application for a HUMS-based credit could readily be developed in compliance with MG-15 based on the LTF elements that were implemented. This may be required if the S-92 program decides to eliminate both the TBO and periodic inspections, based solely on HUMS and BMS monitoring as the primary means of ensuring continued airworthiness. Elimination of the TBO, while continuing periodic inspections, may not require a formal HUMS-based CBM credit, especially if done through a sequence of finite TBO extensions using the same LTF-based approach.

7.4 THE UH-60 OIL COOLER TBO EXTENSION.

In 2006, the U.S. Army extended the UH-60 OCB TBO from 2500 to 3240 hours. The overall procedure, as summarized in reference 7, was similar to the SAC LTF approach. However, the UH-60 OCB TBO extension was executed as an early example of a CBM credit based on U.S. Army Aviation Engineering Directorate (AED) specified requirements. Since Aeronautical Design Standard (ADS)-79 [8] (discussed further in section 8.1.2) did not exist at that time, the U.S. Army AED established a credit validation process using MG-15 as a reference. These U.S. Army AED requirements are as follows:

1. Define the application of the component.

2. Understand the physics of the failure modes and the probability of occurrence through the analysis of the Failure Modes Effects and Critically Analysis (FMECA).

3. Compare the FMECA predicted failures to the actual failures recorded by the maintenance system.

4. Determine the applicable CBM algorithms for monitoring the health of the component.

5. Adjust the inspection and maintenance criteria to support an in-service demonstration.

6. Establish criteria for an airworthiness recertification process.

The above U.S. Army TBO extension procedure for the UH-60 OCB is very similar to the five requirements described in section 7.3.3 for MG-15. AED requirement 1 is the same as MG-15 requirement 1; AED requirements 2 and 3 covered in the MG-15 requirement 2; AED requirements 4 and 5 map to MG-15 requirements 3 and 4; and AED requirement 6 is the same as MG-15 requirement 5.

The application of the AED CBM credit validation process to the example UH-60 OCB TBO expansion is documented in reference 7. ADS-79 has subsequently supplanted the methods documented in reference 7. To receive maintenance credit, the algorithms and sensor combinations must provide high confidence that the fault will be detected. Definitions of direct and indirect evidence were clearly spelled out. Direct evidence is required for credits classified as Hazardous, requiring a combination of seeded fault testing and on-aircraft detection. The primary failure modes were required to have at least five on-aircraft detections and five seeded-fault tests per failure mode.

For lower-criticality credits, indirect evidence is allowed, including analytical methods, engineering judgment, and direct evidence gathered for similar components on other aircraft. Indirect evidence provides the much needed flexibility for qualifying HUMS for TBO extension and credits, which are typically lower criticality.

To confirm HUMS performance for detecting OCB defects, three UH-60A and UH-60L oil cooler fan assemblies, removed due to elevated vibration, were inspected. Teardowns were conducted, and corrosion, pitting, and spalling were shown on all three sets of bearings. The

bearing conditions were therefore defined as moderately damaged. These teardown inspections provided positive confirmations of HUMS capability for fault detection based on vibration data.

In summary, prior to ADS-79, the U.S. Army AED defined a TBO extension and removal process based in part on MG-15 requirements and was able to authorize a TBO extension from 2500 to 3240 hours. Since then (2006), the U.S. Army has steadily developed more comprehensive requirements for general CBM credits, as specified in ADS-79. The TBOs authorized under procedures that predated ADS-79 will be revisited, and new TBO credits will have to be authorized using ADS-79. As described in section 8.1.2, ADS-79 is periodically reviewed and updated. ADS-79B has been distributed for review by a group of experts from the U.S. Army, other DoD services and government agencies, industry, and academia. Currently, ADS-79B specifies more stringent requirements as evidence for HUMS-based CBM credits that may require additional tests or field service data to be collected to sustain the original CBM credit authorized for the UH-60 OCB TBO extension.

8. RESULTS OF RESEARCH OF END-TO-END CBM CREDIT APPROVAL PROCESS IN ACCORDANCE WITH MG-15.

In industry, there is a perception that MG-15 is a barrier to the realization of the potential of HUMS to achieve CBM credits. This was one driver behind the FAA research and development initiative, which funded several other efforts to address the perceived challenges and develop or demonstrate viable approaches to achieve different types of maintenance credits using MG-15-compliant methods. This research effort focused on drive train-related credits and showed that MG-15 contains well-founded material that remains applicable to the certification of HUMS CBM credits. Therefore, although some content of MG-15 could be improved, there is no need to fundamentally change or replace it with alternative material.

It is possible that negative views of MG-15 originated from an inconsistent or inappropriate interpretation of the material by various individuals or organizations. For example, MG-15 clearly provides a mechanism for reducing HUMS qualification requirements (e.g., software design assurance level) through the use of mitigating actions, and in many cases, the ability to use this mechanism will determine the viability of a HUMS CBM credit. However, there is no common agreement on what constitutes acceptable mitigating actions for different CBM credits or how these actions can modify qualification requirements.

This section suggests some improvements be made to MG-15 or additional guidance material be developed. It is recommended that the FAA establish an Industry CBM Working Group, (possibly through the American Helicopter Society) to recommend refinement to MG-15 based on consensus. It is recommended that such a CBM working group build on the results of this and other FAA-funded research and development and provide more specific guidance for viable approaches to comply with MG-15 for different types of credits. This should eliminate issues associated with different interpretations of the MG-15 material.

The following sections identify and discuss other activities related to CBM credit approval, review practical HUMS operational experience, and address possible areas of improvement to MG-15.

In addition to performing a detailed assessment of MG-15, the research effort also generated a set of sample plans to provide further assistance in realizing the CBM credit potential of HUMS. The following example plans are included as appendices to this document:

- Appendix A—Credit Validation Plan
- Appendix B—Example Certification Plan
- Appendix C—Controlled Introduction of Service Plan
- Appendix D—Certification and Technology Transfer Plan

8.1 OTHER ACTIVITIES RELATED TO HUMS CBM CREDIT APPROVAL.

8.1.1 The EASA VHM Working Group.

An European Aviation Safety Agency (EASA) VHM Working Group has produced a Notice of Proposed Amendment (NPA) on VHM. The goal of this NPA is to propose a new certification specification and associated Acceptable Means of Compliance (AMC) covering the design and certification of VHM systems and to amend and enhance existing guidance material on VHM and HUMS to reflect recent technological developments. The AMC sets minimum VHM design and performance standards. It is based on a VHM specification developed by the Helicopter Health Monitoring Advisory Group as a guide to designing, certificating, and operating a VHM system. This group was initiated in the late 1980s, with an international membership from across the industry, and has been actively involved in developing and assisting in the introduction of health monitoring in helicopters. It is intended that MG-15 will be complementary to this AMC.

The EASA VHM WG may review and suggest revisions to MG-15; however, to date, it only recommended that MG-15 is restricted to guidance to achieve airworthiness approval for rotorcraft VHM applications that have a failure effect classified as Major or higher. It was proposed that VHM systems designed in accordance with the new AMC should provide a level of system integrity appropriate for No Safety Effect and Minor effect category VHM applications. These are considered to include VHM applications used to replace functions conducted by portable test equipment without requiring the mitigation of a maintenance verification test flight for standard vibration reduction checks or adjustments (e.g., rotor track and balance, balancing, and absorber tuning).

The reason for the EASA VHM working group proposal is to provide clarification of requirements to approve HUMS functions that are widely accepted, except where there are different interpretations on the need to apply MG-15. Although this motive is understood, it is largely a symptom of inconsistencies in the interpretation and application of MG-15. There is no sound technical reason for a split between HUMS applications with a Minor criticality and those with a Major criticality or higher. A better approach may be to address this issue in the proposed industry CBM working group (the EASA VHM is not considered to have wide enough representation to fulfill this role).

8.1.2 The U.S. Army Document ADS-79 Handbook.

The U.S. Army developed the ADS-79 Handbook [8] to provide guidance similar to MG-15 but for military rotorcraft applications. The Forward of the ADS-79 Handbook states the following:

> "This Handbook describes the Army's CBM system and defines the overall guidance necessary to achieve CBM goals for Army aircraft systems and Unmanned Aircraft Systems (UAS). The Handbook contains some proven methods to achieve CBM functional objectives, but these suggested methods should not be considered to be the sole means to achieve these objectives." [8]

The original ADS-79 was developed by the U.S. Army AED using various source documents as input, including MG-15. Although ADS-79 is used by the U.S. Army, it is still in development. The U.S. Army AED views the Handbook as the document intended to be reviewed and updated on an annual basis, incorporating input from various users (including industry) and lessons learned from the fleet. Several ADS-79 workshops were held to bring together subject matter experts from various parts of the U.S. Army, industry, other government agencies (such as the FAA), and academia. The second revision, Rev. B, was updated with new material, which was reviewed by industry in a workshop setting with follow-on written feedback. At the time of this writing, industry feedback was currently under review by U.S. Army AED for final editing. Versions C and D are planned for the future.

The ADS-79 Handbook is structured with a main body that provides high-level guidance, and seven appendices that provide detailed guidance for the following typical applications or processes:

- Fatigue life management
- Regime recognition
- CI and HI development and validation
- Vibration-based diagnostics
- Data integrity
- Engine and auxiliary power unit CBM
- Structural health monitoring

The appendices provide examples of approaches that could be followed to achieve specific objectives while complying with ADS-79. Appendix E provides an excellent guide for best practices for maintaining data integrity. Additionally, it should be noted that ADS-79B now includes specific guidance on the number of seeded fault tests or field removals needed to validate condition indices. This new guidance is extremely controversial, appears to be inconsistent with the overall philosophy of maintaining baseline risk (see below), and is likely to be clarified in future handbook revisions.

This U.S. Army model is similar to the SAC LTF model because it (1) provides both general guidance and specific compliant examples and (2) it regularly solicits and incorporates user input handbook revisions.

Also, it is recommended that the following two concepts highlighted in ADS-79 be considered for adoption and/or modification for inclusion in MG-15.

(1) The requirement that CBM processes maintain the same or lower risk compared to the as-designed and maintained baseline product risk. This concept of baseline risk acknowledges that

there are inherent, nonzero risks that are addressed by baseline design and maintenance processes. While aircraft are designed and maintenance processes are established to ensure the risk of failure of flight critical components is improbable (or remote, extremely remote, or extremely improbable (using the definitions established in AC 29.1309)), the risk is not zero.

(2) The concept of credible failure modes, which are defined in ADS-79 as "the believable manner in which a system or component may go beyond a limit state and cause a loss of function and/or secondary damage as supported by engineering tests, probabilistic risk analysis, and/or actual occurrences of failures." [8] According to ADS-79, CBM processes must address credible risks as opposed to noncredible risks. The inclusion of similar concepts in MG-15, providing guidance explicitly in the context of nonzero risk, may reduce the ultraconservative interpretation of MG-15 that appears to remain a barrier to industry use of the AC.

8.1.3 The United Kingdom Ministry of Defence CBM Working Group.

The United Kingdom Ministry of Defence CBM Working Group produced a maintenance credit template for the approval of CBM credits. It uses concepts from MG-15, but is based on DEF STAN 00-56 [9]. It requires a Safety Case be developed and maintained that demonstrates how safety is achieved and maintained. All credible hazards and accidents are identified, the associated accident sequences are defined, and the associated risks are determined. All identified safety risks are reduced to levels that are as low as reasonably possible and broadly acceptable.

Key steps in the defined maintenance credit template processes are the disassembly of the current Safety Case, determination of the impact of condition monitoring technology, and reassembly of the Safety Case with the condition monitoring technology implemented. Potential weaknesses in this approach are that the process relies on the preexistence of a detailed safety case (or the creation of one if this does not exist) and the quantification of risks associated with the maintenance credit. Therefore, it is considered that this approach does not offer any clear benefits over MG-15.

The United Kingdom Ministry of Defence CBM Working Group also viewed the requirements for ground stations as troublesome, placing more emphasis on data management and integrity and less on the operating system and hardware. Thus, it is less important if the operating system crashed or the hardware failed as long as the integrity of the data was preserved. The goal was to eliminate the requirement for independent verification of Software of Unknown Pedigree and COTS hardware.

8.2 THE HUMS OPERATIONAL EXPERIENCE.

This section considers lessons from the HUMS operational experience that may have an impact on MG-15. The MG-15 requirements may be a key reason why very few usage credits have been achieved to date. However, this research indicates that other factors are more significant. For example, for health-based credits, a lack of evidence for credit validation can be the primary limiting factor in CBM credit approval. This is due to a lack of feedback from the R&O process, the lack of documented fault case data, and the inadequate capture of HUMS in-service experience. These issues will decrease with the increasing prominence of OEM-supported HUMS.

MG-15 relates integrity requirements, such as software design assurance level to the criticality of the HUMS application. Although this relationship is clearly important, experience has shown that HUMS software has not been a primary integrity issue. Additionally, the implications of applying real-time software design requirements to non-real-time CBM applications are typically overly burdensome and costly compared to the added value relative to more traditional data integrity assurance processes that can be applied to ground-based data processing. In the authors' opinion, ground-based analysis systems that include COTS software, such as HUMS AAD, would improve HUMS effectiveness; therefore, their use should be encouraged by explicitly allowing data quality assurance methods to be used rather than requiring DO-178B certification of ground-based systems. The integrity level of the ground-based system would have to be appropriate for the criticality of the application, and the risks associated with operator-based COTS data processing would have to be adequately addressed.

A high-level system view of HUMS performance and integrity shows that, for health monitoring functions, sensors and aircraft wiring are often the weakest link in the airborne system. Furthermore, the application of AAD technology has highlighted that current HUMS built-in test capabilities may not adequately detect all sensor or wiring faults. Therefore, a key system integrity requirement should be the effective and reliable detection of HUMS sensor and wiring faults to ensure that monitoring capabilities are not compromised.

Another overall system integrity issue is the loss of HUMS data. This may be due to a failure to retrieve data from aircraft deployed to remote locations, damage or loss of removable media used for transferring data off the aircraft, ground-based hardware or network failures, a failure to adequately set up and manage a centralized repository of HUMS data, or a failure to implement a reliable backup policy. Data integrity is important, and appropriate data management standards need to be defined and applied. The risk of data loss or corruption is more serious for usage-based maintenance (UBM) than CBM credits that rely on trending of CIs and health indicators, which can take months before trends become indicative of a critical degradation in component health.

Finally, overall HUMS effectiveness is primarily dependent on the application of reliable alerting criteria (which can include advanced technology such as AAD), the timely investigation of alerts, and the correct response to alerts. The latter two items imply a need to ensure that personnel with the correct skills and experience are available to respond to HUMS alerts and that data are made available to these personnel in a timely manner.

A number of key elements must be in place to successfully exploit HUMS for CBM. Again, it is believed that a lack of some of these elements has hindered the achievement of HUMS CBM credits far more than any deficiencies in MG-15. The elements could be defined under the headings of partnerships, process, and infrastructure and technology. Partnerships relates to the need for cooperation between the OEM, design authority, the HUMS supplier, operators, and other involved parties, such as R&O organizations and Engineering and Asset Management (E&AM) system suppliers when HUMS data are transferred into another system for asset tracking. Process relates to items such as the need for a HUMS exploitation plan with a stepped approach to CBM implementation based on cost benefits and feasibility, the processes for obtaining feedback from R&O organizations and correlating HUMS data with this feedback, and

the processes for the implementation and approval of CBM credits. Infrastructure and technology relates to items such as networked systems for HUMS data transfer, data centralization and web-based access, integration of HUMS and E&AM data, and advanced analysis and data mining technology. Again, an industry CBM working group could establish best practices for all three elements.

One point directly relevant to MG-15 is the classification of evidence for credit validation. Experience shows that there can be a closer correlation of in-service HUMS fault detection evidence from similar components on two different aircraft types than from identical components on an aircraft and in a ground-based test rig. When correlation can be demonstrated, there is a case for classifying fleet experience from another aircraft type as allowable direct evidence for a CBM credit validation.

Finally, note that although HUMS has undoubtedly enhanced helicopter safety, fatal accidents have occurred on HUMS-equipped helicopters. Therefore, the implementation of CBM must not compromise the safety benefits of HUMS. This may be the reason why MG-15 does not cover HUMS applications with Catastrophic criticality. Although such reasoning is understandable, depending on how CBM is applied, there could still be a case for credits on HUMS applications with this criticality level. This may only be pertinent in the future as more experience is gained with implementing CBM credits.

8.3 USABILITY OF MG-15.

The guidance contained in MG-15 is generic in nature. Therefore, it can be difficult to determine what is actually required to achieve a particular CBM credit. This allows flexibility in establishing a compliant process. However, it leaves much open to interpretation. It is recommended that the FAA, in collaboration with an industry CBM working group, produce additional guidance material defining specific MG-15-based certification examples showing viable and compliant methods for achieving particular example HUMS-based CBM credits. In terms of the AC itself, a few enhancements could be made to MG-15 to improve its usability, and a key one of these is briefly discussed here.

MG-15 states that installation, credit validation, and ICA are three basic aspects to HUMS certification, and the certification of HUMS must address all three. It also states that, “these aspects are not totally independent and do have varying interactions with each other” [1]. The interactions are not defined in MG-15. Therefore, from the point of view for certifying a CBM credit, usability could be improved by including a flow chart showing all the elements that need to be addressed in the areas of installation, credit validation, and ICA, and how these are related. Based on an analysis of the contents of MG-15, the flow chart shown in figure 22 was created as an example of what could be included in the AC.

To complement the flow chart, a table could be included to define a generic end-to-end CBM credit approval process. An example is shown in table 22. Elements or tasks included in this process are numbered according to figure 22. Elements numbered 1.x are from the Installation section of MG-15, elements numbered 2.x are from the Credit Validation section, and elements numbered 3.x are from the ICA section.

In addition to producing additional guidance material, the proposed industry CBM working group could also review and enhance the contents of MG-15 in accordance with the recommendations from this research.

Table 22. The End-to-End CBM Credit Approval Process

Requirement/Task	Comments/Description of Activities
Initial Tasks	
1. Description of HUMS application and associated credit	This is the starting point for the CBM credit validation process.
2. Failure Hazard Assessment	An FHA is performed to determine the end-to-end criticality of the desired credit.
3. Resultant end-to-end criticality (Minor, Major, and Hazardous/Severe Major)	The identified criticality level will determine the credit validation requirements.
Credit Validation and Performance Verification	
2.1 Credit validation requirements	A credit validation plan can be produced defining the end-to-end CBM credit approval process.
2.2 Understanding of the physics involved	The first step in the approval process is to demonstrate a clear understanding of the physics of failure—all the credible failure modes that can occur, failure propagation mechanisms and times, the consequences of failure, what failure symptoms could be monitored for, etc.
1.3 Appropriate mitigating actions	Once the physics of failure are understood, any appropriate mitigating actions can be identified. In theory, these could result in a change in the defined criticality level, but are more likely to affect qualification requirements.
2.3 Monitoring requirements and intervention actions	The physics of failure will be used to define monitoring requirements (techniques, sampling rates, alerting method, etc.) and related intervention actions.
1.5 Minimum end-to-end performance criteria	Associated with the monitoring requirements, a set of minimum end-to-end performance criteria will be defined, including installation aspects, such as reliability of sensors, data transfer devices, ground-based equipment, and revisionary strategies.
2.4 Validation methodology	Once the HUMS requirements are defined and the criticality level of the desired credit determines the level of evidence required to validate this, the validation requirements and methodology can be specified.

Table 22. End-to-End CBM Credit Approval Process (Continued)

Requirement/Task	Comments/Description of Activities
Credit Validation and Performance Verification (Continued)	
2.5 Direct evidence (Criticality Hazardous/Severe Major)	Direct evidence for credit validation can be obtained from HUMS in-service experience, seeded fault tests, and on-aircraft trials. When direct evidence is from seeded fault tests on a test rig, there must be a related analysis of operational data variability to validate the visibility of any fault-related indications on operational aircraft. The process must also recognize that direct evidence will accumulate with in-service experience; therefore, there needs to be a continuous feedback mechanism to capture and evaluate this experience. Also, if insufficient evidence is available at the time of initial assessment, there should be an ability to implement the process for advisory purposes only while gathering additional evidence for credit validation.
2.6 Indirect evidence (Criticality Major or lower)	Indirect evidence can be obtained using analytical methods and engineering judgment, together with appropriate validation tests, and also direct evidence from other aircraft types or equipment. The relevance of, and weighting given to, all indirect evidence will need careful assessment. This should include an assessment of the similarity between monitored components, monitoring algorithms, etc.
1.6 Tests to demonstrate performance criteria are met	In addition to validating monitoring algorithms, etc., there is a need to demonstrate that end-to-end HUMS performance requirements are met.
ICA and CIS	
2.7 CIS plan with goals	A CIS plan is required for each CBM credit to be approved. This includes a clear definition of the criteria for successful completion of the CIS phase.
3.1 ICA	Parallel with the development of the CIS plan, an ICA will be produced defining control and operating instructions, rejection criteria and associated actions, mitigating actions, reversionary processes, and a procedure for implementing the CIS. If necessary, the ICA will be refined during the CIS and modified as a result of in-service experience.
2.8 Accumulate data, make refinements and adjustments	During the CIS, evidence of performance will be accumulated and assessed, and any necessary refinements made to the HUMS or associated processes.
2.9 Goals achieved	The CIS phase will be completed once the success criteria have been met.

Table 22. End-to-End CBM Credit Approval Process (Continued)

Requirement/Task	Comments/Description of Activities
In-Service Experience	
2.10 Continued airworthiness and synthesis of credit	A plan is required for continued airworthiness and synthesis of credit, incorporating the three elements described in 2.11-2.13 of MG-15.
2.11 Validate performance of credit through service life	The performance of an approved credit should continue to be validated throughout service use by documenting and reviewing relevant in-service experiences.
2.12 Service experience, engineering evidence from rejected components, etc.	For each CBM credit, a record should be kept of relevant in-service experience, evidence from rejected components, and any new relevant seeded fault test data.
2.13 Required modifications to HUMS application or aircraft component, or opportunities for credit development	An audit or review process is required to assess the need for any modifications to the HUMS application or the monitored aircraft component to enable a credit to be maintained. This process can also be used to identify opportunities for the development of a credit, or for new credits, as direct validation evidence accumulates from the in-service experience.

8.4 INTERPRETATION OF MG-15 REQUIREMENTS.

There are two areas in which interpretation of MG-15 requirements is critical to the achievement of CBM credits and further guidance is needed. These areas are discussed below, and could be further considered by the proposed FAA-established Industry CBM Working Group.

8.4.1 Determining of HUMS Application Criticality.

MG-15 states that the certification process begins with the declared application intent and determination of the resultant criticality [1]. If the application is for credit, the end-to-end criticality for the application must be determined and used as an input to establish the application qualification requirements. The criticality describes the severity of the end result of a HUMS application failure or malfunction. Criticality is determined by performing an FHA that considers the safety effect that the HUMS application has on the aircraft. This determines what undesirable effects can occur as a direct or indirect result of using HUMS for maintenance or operational actions.

It is important that the correct criticality level is determined for a HUMS application. If the criticality level is too high, it may unnecessarily prevent obtaining a CBM credit. Conversely, if it is too low, it may result in an inadequate definition of integrity requirements. Careful interpretation is required to determine the correct criticality level. For example, it is necessary to carefully consider the answer to the following question: Is the criticality of a HUMS application the same as the criticality of the failure of the monitored component? The answer may be yes in certain circumstances and no in others.

A key consideration is whether HUMS detection is the last line of defense for a flight critical failure mode. If HUMS is the last line of defense and a false negative could lead to an in-flight failure with no other means of detection, then criticality of the credit would likely be equal to the criticality of component failure. However, the credit analysis can consider compensating provisions inherent to the design approach, physics of failure progression, and other manifestations that are detectable within the cockpit in the same manner as is currently done in typical FMEA used to substantiate the design of flight critical components.

Another consideration is whether the HUMS credit is one of multiple factors to extend a TBO or the primary factor in eliminating a TBO. The U.S. Army's ADS-79 [8] provides specific guidance regarding different requirements for the two scenarios. If a component is to be placed on-condition solely as a result of the implementation of a HUMS mechanical diagnostics function, it is appropriate that the criticality of the HUMS function is equivalent to the criticality of the end effect of the failure of that monitored component. However, the same HUMS function may be awarded some credit for monitoring one or two failure modes in the extension of a TBO period that also controls other failure modes. Here, the assessment may also take into account component reliability information as used traditionally in TBO development and extension programs and the fact that the TBO is being extended but not eliminated. It could be argued that the criticality level of the HUMS application could be lower as the TBO has only been extended, and there is an established process for doing this without HUMS. HUMS could provide risk mitigation for a traditional TBO extension decision. An alternative position would be to use the traditional approach to a TBO extension along with a HUMS application as a mitigating action. This would reduce the qualification requirements for HUMS and develop sufficient direct evidence to validate a HUMS credit through a sequence of TBO extensions.

It is recommended that further guidance material be generated by the proposed FAA-established Industry CBM Working Group to provide guidance regarding determination of HUMS application criticality, including some specific examples.

8.4.2 Appropriate Mitigating Actions and How They Modify Qualification Requirements.

It was stated earlier that mitigating actions can reduce HUMS qualification requirements, which may determine the viability of a HUMS CBM credit; therefore, further interpretation guidance is desired. This guidance must be specific to different types of application, as appropriate mitigating actions will vary depending on the application. For example, there may be greater scope for applying mitigating actions to one type of CBM credit than there is to another type of credit. Therefore, it could be possible to have a situation where two HUMS credit applications have the same criticality classification, but as a result of the differing scope to apply mitigating actions, the acceptable software levels for the credit applications are different.

To enable the effective use of MG-15 to achieve CBM credits, it is important that there is common agreement on what constitutes acceptable mitigating actions for different CBM credits and how they can modify qualification requirements. Therefore, it is again recommended that further guidance material is generated by the proposed Industry CBM working group on the application of mitigating actions, including specific examples.

8.5 HEALTH VS USAGE MONITORING.

The two primary differences between UBM credits and health or CBM credits are (1) the types of data required and (2) the criticality of data integrity. The two are interrelated. The end-to-end process for both UBM and CBM credits includes measurements from their respective sensors, and one must address the need for sensor reliability and data integrity from the point of measurement to the point of final data processing and end use.

UBM credits in the short term typically require only aircraft parametric data needed for regime recognition and other derived parameters (e.g., estimated gross weight, center of gravity, or loads). The sources of the data are typically existing sensors needed to support other flight critical applications (e.g., flight control), requiring these sensors to be highly reliable for use with other Level A or B systems. In modern aircraft where the data are available on a digital bus, HUMS can extract the data with no impact on data quality and reliability, and hence, HUMS applications simply need to ensure the data integrity. On older aircraft in which the HUMS has to tap into analogue wiring harnesses, risk of data corruption exists, especially on retrofitted HUMS, which has to be addressed during installation validation.

On the other hand, CBM credits typically require measurements from physical sensors not required for any other aircraft function (e.g., vibration) in the short-term and other sensors (e.g., crack gages) in the long term. Thus, HUMS CBM installation and credit validation have to place more emphasis on sensor validation, including reliability, data quality, and data integrity at the point of measurement. In the long term, UBM credits may use measurements from unique physical load sensors (e.g., main and tail rotor torque sensors and rotor loads) and then will share similar burdens.

There will always be uncertainty in the usage monitoring of life-limited components, and this is accounted for in the factors of safety applied to component lives. Any reduction in uncertainty through more accurate usage monitoring should enable a credit to be gained in the form of an adjustment to the factor of safety. To gain a credit, usage monitoring does not need to be 100% accurate, simply more accurate than the current methodology. However, it is not possible to determine how much usage a component has been exposed to by inspecting this, unless a fatigue crack has developed, as there is no visible evidence of the amount of fatigue damage a component has accumulated. Therefore, for usage monitoring, component inspections typically cannot be used as effective mitigating actions.

For health monitoring, component reliability is an important consideration when determining the suitability of a health-based credit. The traditional process of developing TBOs is based on reliability data, and a gearbox could be considered to be on-condition if, in a large majority of cases, it is rejected for defects before it reaches its TBO life. Unlike usage, component health can be determined through inspections; therefore, these can be used as mitigating actions when determining qualification actions. It should be recognized that current inspection regimes may not be 100% effective, and a health function could qualify for credit if it can be shown to be more effective than the current approach.

Neither UBM nor CBM credits are envisioned in the short term to influence pilot real-time, time-critical, decision-making processes. Rather, both influence maintenance decisions with

lead times of at least 10, and ideally greater than 50-100, flight hours to be useful for CBM credits and years for UBM credits. Therefore, software criticality levels and requirements originally developed to address the impact of software malfunctions on real-time operation of the aircraft are somewhat inappropriate for HUMS applications. This is especially true for UBM credits, which typically are deterministic and provide ample time for off-board data quality assurance by the rotorcraft OEM. It is less true for CBM credits that monitor more stochastic, unpredictable phenomena and, from a practical standpoint, require decisions to be made by operators or maintainers, or perhaps, third parties with less time and less expertise to assess data quality before making a decision. In both cases, onboard data acquisition is critical to ensure the integrity of the source data.

From the perspective of data criticality, both UBM and CBM applications can, and should, leverage the DO-178B software criticality definitions and requirements. If a maintainer uses HUMS data to decide erroneously to leave a flight critical part on the aircraft that is actually not flightworthy, the impact could indeed be hazardous regardless of whether it is based on a UBM or a CBM credit. For UBM credits, the emphasis must be placed on ensuring data integrity, demonstrating that any loss or corruption of data can be identified and mitigated before a UBM credit is calculated and applied. Mitigation is straightforward, replacing missing data using conservative assumptions and factors of safety on credits allowed.

For CBM, temporary loss of data is less important as long as it can be demonstrated that the features used for determining the condition or health monotonically increase or decrease with part degradation and that fault progression times are much longer in time scale than potential temporary loss of data. The ability to detect and repair or replace a degraded sensor should be addressed. Similar data integrity assurance processes developed for UBM would be applicable to CBM. The emphasis for CBM should be more on probability of detection, false-alarm rate, and the separation between healthy and unhealthy components using appropriate thresholds. Thus, CBM depends on seeded fault tests and fleet data analysis, which are critical to CIS. This can be a very expensive and time-consuming endeavor, which is not a factor for UBM.

8.6 CRITICALITY ASSESSMENT.

The certification process begins with the declared application intent and determination of the resultant criticality. If the application is for credit (i.e., it adds to, replaces, or intervenes in maintenance practices or flight operations), the end-to-end criticality for the application must be determined and used as an input to establish the application qualification requirements.

The criticality describes the severity of the end result of a HUMS application failure or malfunction. Criticality is determined by performing an FHA or FMEA that considers the safety effect that the HUMS application can have on the aircraft. The FHA is typically a top-down assessment at the system level; whereas, the FMEA focuses on specific failure modes at a component level. The FHA and FMEA determine what undesirable effects can occur as a

direct or indirect result of using HUMS for maintenance or operational actions. The level of severity associated with this effect will result in assigning one of the following five levels of criticality:

"(i) Catastrophic: Failure conditions, which would prevent continued safe flight and landing.

(ii) Hazardous/Severe Major: Failure conditions, which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

(A) A large reduction in safety margins or functional capabilities,

(B) Physical distress or higher workload such that the flight crew could not be relied on to perform their tasks accurately or completely, or

(C) Adverse effects on occupants including serious or potentially fatal injuries to a small number of those occupants.

(iii) Major: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.

(iv) Minor: Failure conditions which would not significantly reduce aircraft safety, and which would involve crew actions that are well within their capabilities. Minor failure conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload such as routine flight plan changes, or some inconvenience to occupants.

(v) No-Effect (Non-hazardous class): Failure conditions which do not affect the operational capability or safety of the aircraft, or the crew workload." [1]

MG-15 does not address systems in the Catastrophic criticality category, therefore, if any credit is to be gained, the general guidelines for determination of criticality levels will be either Minor, Major, or Hazardous/Severe-Major.

It has been suggested that determining credit approval requirements from a criticality assessment based solely on the consequences of a monitored component failure and with only a few criticality categories is overly restrictive and cannot be applied to all cases. One alternative to CBM credit approval that has been proposed is to base this on an overall risk assessment. A safety case would be developed for each proposed HUMS CBM credit, with credit approval requiring a demonstration that an alternative HUMS-based approach to maintaining airworthiness results in the same or lower risk than the current approach using overhauls and

manual inspections. The risk-based approach may be an appropriate alternative, which could allow credits to be prudently defined when at face value it may seem infeasible using a criticality assessment approach.

If a component is placed on-condition as a result of the implementation of a HUMS mechanical diagnostics function, it is appropriate that the criticality of the HUMS function is equivalent to the criticality of the end effect of the failure of that monitored component. This takes into account compensating provisions that are inherent to the design or residual maintenance practices after the credit is defined. However, if the same HUMS function is awarded some credit in the extension of a TBO or inspection period, with that assessment also taking into account component reliability information (as is used traditionally in TBO development programs), a risk-based approach may seem more appropriate. An alternative position could be to consider the joint use of traditional information in a TBO extension decision, together with the TBO not being eliminated completely, as mitigating actions to reduce the qualification requirements for HUMS.

Although the motivation for using a risk assessment process for credit approval can be understood, this lacks the simplicity of the current criticality assessment, and the interpretation of MG-15 regarding the impact of mitigating actions on qualification requirements should be fully explored before considering this further. It is recommended that MG-15 be augmented to include a discussion regarding the viability of such an approach.

8.7 QUALIFICATION REQUIREMENTS FROM CRITICALITY ASSESSMENT.

The criticality level drives the HUMS certification requirements. For example, when a HUMS application is classified as Hazardous/Severe Major, then direct evidence must be gathered for credit validation. Similarly, DO-178B directly relates the required Design Assurance Level for software development to the system criticality level, i.e., Level A for Catastrophic, B for Hazardous, C for Major, D for Minor, and E for No effect.

If tail rotor drive system components have a criticality level of Hazardous/Severe Major, then a simplistic review and application of MG-15 would conclude that any HUMS tail rotor drive system health credit would require Level B software and a potentially large-scale and expensive seeded fault rig test program to demonstrate that HUMS can detect all the relevant failure modes. This approach can result in the MG-15 being perceived to be a barrier to HUMS CBM credits.

The above assessment overlooks an important concept of mitigating actions in MG-15, which is considered critical to the practical achievement of HUMS CBM credits. A mitigating action is defined as an autonomous and continuing compensating factor that may modify the level of qualification associated with certification of a HUMS application. Under the heading of certification approach, MG-15 states that it must be possible to demonstrate that the integrity level of the system is compliant with the established criticality level, and that this may be achieved by a combination of application qualification plus appropriate mitigating actions. Under the heading of installation, MG-15 states that the final level of equipment qualification may not only be the result of technical considerations, but also the result of other mitigating actions, of which there are many types [1]. Many of these actions can result in a reduction of qualification levels for equipment.

A key area of direct research into MG-15 is in interpretation of the contents of the AC with regard to mitigating actions and their potential impact on qualification requirements. One obvious area is in the requirement for software qualification levels, and MG-15 incorporates a flow chart illustrating the process for determining if the required DO-178B HUMS application software certification level can be mitigated. There are similarities between mitigating actions and the use of independent verification means for the qualification of ground-based COTS software; therefore, these are considered together.

It is difficult to achieve nontrivial HUMS-based CBM credits using many existing in-service systems unless it is possible to mitigate requirements for software certification levels. It is reasonable to consider the use of mitigating actions to reduce software design assurance levels, given the fact that HUMS in-service experience shows that undetected sensor and instrumentation issues can pose a much greater source of risk than the design assurance level of the software. Similarly, overall system effectiveness is most important, especially because viable credits do not affect real-time decision making by the crew. HUMS credits are based on the principal of detecting faults with sufficient lead time (at least 10, ideally greater than 50 to 100, flight hours) to avoid unnecessary downtime by preplacement of parts and secondary damage. Thus there is ample time to apply quality assurance checks and mitigating actions to ensure the integrity of the decision-making process, which can be performed in a ground-based environment. Therefore, practical approaches to qualify ground-based software are desired to allow the use of sophisticated analyses and the early transition of advanced methods, which would lead to increased system effectiveness. The demonstrated benefits of ground-based processing can be lost due to unnecessary restrictions related to the use of COTS hardware and software environments. An overall system risk assessment could be included as part of a system qualification process.

It should be possible to make a clear distinction between health and usage monitoring in the software requirements area. A case can be made for requiring a lower software design assurance level for health monitoring functions than for some usage monitoring functions because it is possible to independently verify component health, but is not always possible for usage. (Usage functions, such as recording of flying time or number of takeoffs and landings that can be readily independently verified, are excluded from this argument).

For health monitoring functions, a range of actions can be considered to mitigate qualification requirements. These include physical inspection of component condition, together with various acquired signal and processed data checks, and specific checks to be performed after software modifications.

A typical HUMS could have its software written to different levels depending on the mitigating actions and application (usage versus health). For example, if the credit criticality were Major, then the software would need to be written to Level C; however, for this credit criticality, the health data may actually only need to comply to Level D because the HUMS data can be correlated to findings during inspections and routine maintenance actions.

MG-15 is very restrictive regarding ground-based software used by operators. This is considered appropriate because the typical operator would not have the expertise to independently validate

the results of complex algorithms. Further, for practical reasons, e.g., cost, such GSS, are not likely be certified to higher than Level D. Thus, from a practical standpoint, UBM/CBM credits dependent on GSS data processing should be restricted to lower-criticality credits unless the OEM is involved in data quality assurance and risk mitigation.

It is also thought that OEM risk-mitigating processes should enable more flexibility with regard to off-board software certification for ground-based calculations of credits by the OEM. The assessment of whether the end-to-end process is MG-15 compliant should be based on an assessment of data integrity assurance and maintenance of baseline risk rather than rigid application of DO-178B guidance to non-time-critical, decision-making processes. The OEM should be able to use a computational environment and processes for HUMS-based credits similar to that used for original design calculations and substantiation.

8.8 CREDIT VALIDATION.

MG-15 relates the requirements for obtaining evidence for credit validation to the criticality level of the HUMS application. For example, it states that when this is classified as Hazardous/Severe Major, then direct evidence must be gathered [1]. The best direct evidence will be actual service experience on HUMS-equipped aircraft; however, obtaining this can involve an indeterminate period of operations because relevant component failure modes must have occurred and been detected. Alternative methods of gathering direct evidence are aircraft trials and seeded fault rig tests.

The credit validation section of MG-15 does not consider mitigating actions, but it is still possible to consider actions that could mitigate credit validation requirements. As discussed previously, an integrated approach could be defined, with progressive increases in TBOs or inspection periods based on a combination of HUMS and traditional reliability assessment processes. It may be that there is validation evidence for some, but not all, of the failure modes controlled by the current TBO and inspection approaches, and this can be factored into extension decisions.

Even if it is not direct evidence of the detection of a particular failure mode on a specific aircraft component, much can be learned from in-service HUMS experience that could provide an input to credit validation; for example, the general correlation of HUMS data with the condition of components removed for overhaul. Similarly, using the assessment processes defined in the credit validation plan (see appendix A), some indirect evidence could be considered equivalent to direct evidence if this originates from an off-aircraft source such as a test rig.

The health monitoring function could ultimately be used to extend the OCB TBO or to put the OCB on CBM. In the case of the TBO extension, the HUMS can be used to provide the delta to the traditional growth process; for example, LTF and reliability data could be used to qualify the delta. However, the use of HUMS for on CBMs would have to rely solely on HUMS data and any mitigating actions.

8.9 RECOMMENDATIONS ON ADDITIONAL REQUIREMENTS FOR MG-15.

Section 8.2 identified some areas where more specific MG-15 guidance would be helpful. The most significant area is data quality assurance. Some relevant requirements and guidance can be found in DO-200A [10] and ADS-79 Appendix F [8]. The DO-200A provides the minimum standards for the processing of aeronautical data that are used for navigation, flight planning, terrain awareness, flight simulators, and other purposes. The standards cover data processing quality assurance and quality management requirements and provide the user the necessary assurance that aeronautical databases meet the appropriate quality requirements for the data. DO-200A supports new technology and the expanding scope of aeronautical data by providing a more structured approach to the extremely important issues of data quality and data integrity management. Data quality requirements include accuracy, precision, assurance level, format, timeliness, completeness, and traceability. ADS-79 guidance is based on multiple sources and is specific to HUMS applications.

It is recommended that the proposed FAA-initiated Industry CBM Working Group review the areas identified in section 8.2 where MG-15 could be improved and refine MG-15 accordingly.

9. CONCLUSIONS.

GE Aviation Systems, LLC and Sikorsky Aircraft Corporation (SAC) researched the end-to-end process for approving an example Health and Usage Monitoring System (HUMS) Condition-Based Maintenance (CBM) credit in accordance with the requirements of Federal Aviation Administration (FAA) Advisory Circular (AC) 29-2C Miscellaneous Guidance (MG)-15. MG-15 covers three areas: installation, credit validation, and Instructions for Continued Airworthiness. This research focused primarily on credit validation, with the primary goal of assessing the suitability of the guidance material contained in MG-15 for obtaining a CBM credit.

A generic analysis of HUMS CBM credit potential was initially performed to assess the current credit status of HUMS, and the feasibility of different candidate CBM credits for HUMS mechanical diagnostics. Using this generic analysis, together with a semiquantitative ranking matrix, the target CBM credit for the research was selected. This was an extension of the time between overhaul (TBO) on the oil cooler for the S-92, which in turn, requires an extension of the replacement interval for the oil cooler bearings (OCB). Following a failure hazard assessment, the highest level of criticality of the credit was identified as Major. The analysis also identified the OCB failure modes that need to be detected.

A validation methodology was defined, based on the use of a combination of direct and indirect evidence. A credit validation plan was developed that included a technical justification for the use of different types of evidence to support the CBM credit validation. A rig test plan was defined, and a number of rig tests were conducted to generate additional OCB credit validation evidence. These tests included a number of seeded fault tests with corroded bearings, simulated assembly damage, light spalling, a cage crack, and degreased bearings.

A key element of the research was to demonstrate and validate the ability of HUMS algorithms and methodologies to detect incipient mechanical faults and facilitate timely maintenance

intervention. The research focused on the application of vibration health-monitoring techniques to the S-92 OCBs. The analysis performed was extended beyond that required purely for credit validation to include a wider assessment of bearing monitoring capabilities and how these could be optimized to provide the greatest CBM credit potential. The analysis included a comparative assessment of the bearing monitoring system (BMS) frequency Band 0 and Band 1 vibration data; an assessment of alternative frequency bands; an analysis of the BMS temperature data; the application of more sophisticated signal-processing techniques to the vibration data; and an analysis of the influence of sensor location on fault detection performance. The results confirmed that the BMS Band 0 data, with the current HUMS monitoring threshold of 0.75 g, have the potential to detect a range of bearing faults before they reach a critical condition.

The research showed that the existing BMS has the potential to provide the target OCB CBM credit. A credit application could therefore be made in accordance with MG-15, and examples of the required supporting plans for introduction to service and continued airworthiness have been generated. During this 5-year FAA research program, the OCB TBO was independently extended from 2500 to 3500 hours using the traditional lead the fleet (LTF)-based approach. As additional input to the research, the process that was used to obtain the TBO extension was compared to the requirements of MG-15. It showed that there was considerable synergy between the LTF-based approach and the requirements of MG-15, and that the process developed would satisfy many of the key MG-15 requirements.

The practicality and usability of MG-15 were assessed in this research, which showed that the AC contains well-founded material that remains applicable to the certification of HUMS CBM credits. Therefore, although some MG-15 content could be improved, there is no need to fundamentally change or replace it with alternative material. Suggestions have been made for improvements to MG-15 and the development of additional guidance material. It is recommended that the FAA establish an Industry CBM Working Group, possibly through the American Helicopter Society, to recommend agreed upon refinement to MG-15. It was recommended that such a CBM working group build on the results of this and other FAA-funded research and development and provide more specific guidance for viable approaches to comply with MG-15 for different types of credits. This should eliminate current issues associated with different interpretations of the AC material.

10. REFERENCES.

1. AC 29-2C MG-15, “Airworthiness Approval of Rotorcraft Health and Usage Monitoring Systems (HUMS).”

2. SER-920067, “Fatigue Evaluation and Design Assessment of Structure for S-92 Drive System,” Sikorsky Aircraft Corporation, March 8, 1997, most recent revision October 24, 2003.

3. RTCA/DO-178B, “Software Considerations in Airborne Systems and Equipment Certification,” December 1, 1992.

4. SER-920272, “FAA Certification Plan for the Health and Usage Monitoring System (HUMS),” Sikorsky Aircraft Corporation, June 28, 2003.

5. SER-920829, “S-92A HUMS Certification Test Plan for FAA Credit,” Sikorsky Aircraft Corporation, November 30, 2003.

6. SA S-92A-AMM-000, “Aircraft Maintenance Manual for Sikorsky Helicopter Model S-92A,” Sikorsky Aircraft Corporation, last revised December 2009.

7. Suggs, Daniel and Wade, Daniel, “Vibration Based Maintenance Credits for the UH-60 Oil Cooler Fan Assembly,” *AHS CBM Specialists Meeting*, Huntsville, Alabama, February 2008.

8. ADS-79, “Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for US Army Aircraft,” February 17, 2009.

9. “Safety Management Requirements for Defence Systems,” DEF STAN 00-56, Issue 4, UK Ministry of Defence, June 1, 2007.

10. RTCA/DO-200A, “Standards for Processing Aeronautical Data,” September 28, 1998.

APPENDIX A—CREDIT VALIDATION PLAN

A.1 SCOPE.

This section provides a credit validation plan for the Sikorsky S-92® oil cooler Condition-Based Maintenance (CBM) credit described in the main report and provides the basis for the data acquisition and analysis described in this appendix. This plan complies with Advisory Circular (AC) 29-2C Miscellaneous Guidance (MG)-15 [A-1], but assumes that the requirements for the first aspect of Health and Usage Monitoring System (HUMS) certification, i.e., installation, have already been addressed on the basis of an assessment of the criticality of the full range of HUMS applications. Installation includes all the equipment needed for the end-to-end application that is associated with acquiring, storing, processing, and displaying the HUMS application data, including airborne- and ground-based equipment. The criticality assessment provides an input to establish system integrity criteria and determines the depth of requirements for certification. The range of applications will also have minimum end-to-end performance criteria consistent with their intended use. These criteria include accuracy, timing/sampling, resolution, event recognition, and consistency. Information generated as part of a credit validation process may have an impact on the installation requirements, including the data integrity of the HUMS ground station and any associated analysis tools.

The installation aspects of a HUMS certification should address items, such as descriptions of all the monitoring functions and algorithms; how data are collected, displayed and interpreted; and the definition of requirements for system qualification tests. For example, these would include tests to demonstrate the correct functioning of all sensor interfaces, the proper calculation of vibration condition indices (CI), and the end-to-end process from HUMS sensors to ground-based equipment.

MG-15 states:

> "HUMS applications for which credits are sought must be validated. The validation process would generally need to include the following:
>
> - Description of application and associated credit.
> - Understanding of the physics involved.
> - Validation methodology.
> - Introduction to service.
> - Continued airworthiness (synthesis)." [A-1]

The credit validation plan follows this list of required documentation. Subsequent sections address each requirement. This section documents the plan, not the results of implementing the plan, and explains how it complies with MG-15.

A.2 THE HUMS APPLICATION AND ASSOCIATED CREDIT.

The application that is the subject of this credit validation plan is the vibration-based HUMS mechanical diagnostics function for the S-92 oil cooler bearings (OCB). The associated credit is

the extension or elimination of the 3500-hour TBO of the oil cooler, which translates to an extension or elimination of the 3500-hour replacement time of the OCBs. A failure hazard assessment determined that the associated level of criticality was Class III (Major) effect. The system installation integrity requirements discussed in section A.1 must be compatible with this criticality level.

A.3 PHYSICS OF FAILURE AND HUMS APPLICATION REQUIREMENTS

This section defines the requirement to provide evidence that the physics involved in the CBM credit application are understood, and therefore, appropriate monitoring techniques, algorithms, and CIs; rejection criteria; and associated intervention actions are selected.

A.3.1 PHYSICS OF FAILURE.

For the requested credit, evidence must be provided that both the mechanisms of failure and rates of failure progression are understood, and therefore, that the monitoring requirements and the point at which intervention action is necessary can be determined.

A.3.1.1 Failure Mechanisms.

Only the oil cooler system failure modes related to its bearings need to be considered for the target credit as defined above. Thus, only the bearing failure modes are considered here. The key element of the requested credit is an extension or elimination of the 3500-hour replacement time of the two S-92 OCBs.

The following mechanisms of failure or degradation for rolling element bearings are defined as:

1. Surface contact fatigue causing ball or raceway pitting, spalling and/or cracking, and ultimately bearing failure

2. Corrosion causing ball or raceway pitting and wear, and ultimately bearing failure after a prolonged period

3. Degradation of lubrication (grease) causing ball or raceway pitting and wear, and ultimately bearing failure after a prolonged period

4. Ball sliding and skidding causing raceway wear, or increased bearing temperatures and bearing failure if severe (this could be related to mechanism 5)

5. Cage failure causing a loss of ball location, ball contact, increased bearing temperatures, and bearing failure

6. Loss of lubrication (grease) causing ball and raceway damage, increased bearing temperatures, and bearing failure

7. Assembly fault or manufacturing defect causing bearing wear, ball skidding, increased bearing temperatures, and bearing failure

Only age-related failure mechanisms are controlled by the 3500-hour bearing replacement; therefore, mechanism 7 above should be considered in terms of how it may accelerate the other failure mechanisms. The bearings are sealed and do not require any periodic lubrication. In addition, the 50-, 250-, and 500-hour oil cooler inspections include a requirement to check the bearings for evidence of purged grease. These are mitigating factors for failure mechanism 6.

There is a large amount of published literature on bearing failure mechanisms; therefore, no new theoretical analysis is required for credit validation. However, for a particular bearing, the actual failure mechanisms experienced can be dependent on the bearing design, function (e.g., the type of component being supported), and its location and environment. For example, an OCB may be susceptible to corrosion due to its external location, but not to surface contact fatigue and spalling due to the low surface contact stresses resulting from its relatively light loading. In contrast, a bearing supporting a main drive train gear may experience surface contact fatigue and spalling due to high loading, but not corrosion due to its internal oil-wetted location. Therefore, the physics of failure assessment shall include a review of relevant in-service experience to identify the failure mechanisms that have occurred in-service, together with the relative frequency and consequences of each mechanism.

A.3.1.2 Review of Relevant Sikorsky Aircraft Corporation OCB Experience.

Sikorsky Aircraft Corporation's (SAC) S-92 and UH-60 OCB experience shall be reviewed relative to the S-92 bearing failure modes. The S-92 failure modes consist of five major categories: seal problems, phenolic cage faults, raceway faults, balls faults, and grease issues. Each major category can be further categorized by failure types. SAC's experience is summarized in table A-1. The table also includes the probability of occurrence, a timeline for the failure mode occurrence relative to other failure modes, indication if the failure mode is caused by a manufacturing issue or a fatigue/debris issue, the most likely candidate for detection of the failure mode, and whether the failure mode has been observed in the S-92 or UH-60 fleet.

Table A-1. The SAC OCB Experience

Failure Category	Failure Type	Probability (L, M, H)	Criticality	Timeline	Manufacturing Issue	Fatigue/ Debris Issue	Detection		Observed in S-92 Fleet	Observed in UH-60 Fleet
							Vibrations	Temperature		
Seal problem	Indented	L	Minor	1	X		X		X	N/A, shielded
	Cracks, wear	L	Minor	1		X				N/A, shielded
Phenolic cage fault	Cracks	L	Minor	2		X				N/A, steel
	Breaks	L	Major	3		X	X	X		N/A, steel
Raceway fault	Light to medium spalls	M	Minor	2		X	X		X	
	Light to medium corrosion/pits	M	Minor	2		X	X		X	X
	Severe corrosion/pits	L	Minor	3		X	X			X

Table A-1. The SAC Oil Cooler Bearing Experience (Continued)

Failure Category	Failure Type	Probability (L, M, H)	Criticality	Timeline	Manufacturing Issue	Fatigue/ Debris Issue	Detection		Observed in S-92 Fleet	Observed in UH-60 Fleet
							Vibrations	Temperature		
Ball fault	Dents	L	Minor	1	X		X		X	
	Light to medium spalls	L	Minor	2		X	X			
	Light to medium corrosion/pits	M	Minor	2		X	X		X	X
	Severe corrosion/pits	L	Minor	3		X	X			
Grease issue	Contaminated/degraded	M	Minor	1		X				X
	Loss of lubrication/oxidized	L	Major	3		X	X	X		

L = Low M = Medium H = High

A.3.1.3 Specification of Failure Mechanisms to be Detected for S-92 Oil Cooler CBM Credit.

Based on the information in the previous sections, the failure mechanisms that must be detected to enable the S-92 oil cooler CBM credit to be obtained shall be specified.

A.3.1.4 Failure Progression Rates.

There is a substantial body of rig test evidence to show that, depending on the complexity of a mechanical system, bearing failure progression rates can be very difficult to accurately predict from theoretical analysis. This is due in part to unknown factors, including material or manufacturing defects, or assembly problems, such as a misalignment. However, although bearing load is a factor, the failure progression rate has a clear dependency on the type of failure mode that occurs. For example, failure mechanisms 1-4 in section A.3.1.1 involving sliding, wear, pitting, and spalling, normally have a relatively slow failure progression rate, but can ultimately result in bearing failure. However, failure mechanism 5 can progress relatively rapidly to a bearing failure, as can failure mechanism 4 in cases of severe ball skidding.

Failure progression rates must be estimated for the bearing that is the subject of the CBM credit and for the failure mechanisms that must be detected. These rates should be estimated in terms of the opportunity to take corrective action, e.g., within a flight (where there is no opportunity for corrective maintenance) or within the appropriate number of flight hours. For each relevant failure mechanism, the failure progression information should then be used to determine the size or extent of a defect that must be detected. This must be sufficiently in advance of the point of bearing failure to enable corrective action to be taken before any airworthiness issues could arise.

A.3.2 THE HUMS APPLICATION REQUIREMENTS.

A.3.2.1 HUMS Techniques.

Applicable HUMS techniques for rolling element bearings are

- vibration monitoring
- oil debris monitoring (for oil-washed bearings only)

- temperature monitoring

Oil debris monitoring can only be applied to bearings within gearboxes in which there is an oil supply to transfer debris to a detection device. Because of the close proximity of other sources of vibration, these bearings are more difficult to monitor using vibration analysis than bearings on external shafts. In this sense, oil debris and vibration monitoring are very much complementary techniques.

For the S-92 OCBs that are the subject of the CBM credit validation, the applicable techniques are vibration and temperature monitoring. The S-92 HUMS BMS implements both techniques. Increased bearing temperatures are normally a relatively late indication of impending bearing failure, and the FAA HUMS research focused primarily on investigating the CBM credit potential of vibration-based mechanical diagnostics for rolling element bearings. Therefore, temperature monitoring was considered only as a compensating provision, and the research attempted to determine to what extent this was required.

Empirical and analytical models should be used to determine the effects of a propagating failure mechanism on the monitoring data being acquired. For the vibration monitoring of mechanical systems, the approach should be to initially define this in qualitative terms. For example, it is possible to determine the qualitative impact of different failure modes on bearing vibration as follows:

- All faults involving damage to the bearing raceways or rolling elements will cause some increase in the overall vibration energy; however, the magnitude of this energy is normally low compared to other sources of vibration, such as gears.

- Bearing defects, such as localized pitting or spalling of the raceways or rolling elements, will generate impulsive signals, with repeating patterns correlated with the timing of surface contacts with the localized damage.

- General or distributed bearing damage can raise the background white noise level of a vibration signal.

- Experience has demonstrated that the maximum frequency range required for bearing vibration monitoring is 0 to 40 kHz. Within these limits, some directly relevant experience is required to determine the best frequency range for a particular application. High-frequency vibration signals attenuate more rapidly with distance than low-frequency signals. Therefore, a generic statement can be made that, for a sensor in close proximity to a bearing, early defects may be first detected at higher-frequency ranges where there is less interference from other vibration sources. However, as the damage propagates this will become more visible at lower frequency ranges, due to both the changing characteristics of the vibration generated by the damage, and also to its increasing amplitude.

In addition to the above characteristics, bearing failure mechanisms causing increased vibration and abnormal loads can ultimately result in accelerated wear and increased bearing play and shaft motion, which leads to excessive oil cooler vibration.

There are different approaches to bearing vibration monitoring within HUMS. As described in section A.2, the oil cooler BMS in the S-92 HUMS performs one per revolution (i.e., 1/rev) and two broadband vibration measurements at a 1-Hz rate. GE Aviation's generic HUMS (GenHUMS) performs a less frequent, but more computationally intensive analysis, comprising a periodically scheduled band-passed and enveloped vibration signal power spectrum analysis, with defect pattern matching. The S-92 HUMS implements a similar technique for monitoring bearings within gearboxes.

For the purpose of the FAA HUMS research, a generic approach was taken to the definition of the vibration-monitoring technique. Therefore, when there were differences in specific measurements, the technique was defined in terms of the monitoring particular elements and features of a vibration signal. Therefore, the appropriate definition of the bearing vibration-monitoring technique is:

- Measurement of the shaft order vibration. For the S-92 BMS, this is 1/rev vibration. For the GenHUMS, it is 1/rev, 2/rev, and 3/rev vibrations.

- Measurement of vibration energy levels within specified frequency bands. For the S-92 BMS, this is average vibration energy levels in the frequency bands of 1.5 to 5 and 15 to 20 kHz. For the GenHUMS, the frequency bands are fully configurable up to a 40-kHz limit; however, all analyses will include the frequency bands specified for the BMS. In addition to an overall energy measurement, the GenHUMS separately calculates the energy in the tones and base of a Fast Fourier Transform of the band-pass filtered data. (The tones relate to repeating impulsive events in the signal, and the base to the white noise content of the signal).

- For the GenHUMS only, measurement of specific defect patterns in the vibration data associated with localized defects on the inner race, outer race, and rolling elements, can be predicted from a knowledge of the bearing geometry.

A.3.2.2 Alert Limits.

The size or extent of a defect that must be detected by the HUMS vibration monitoring must be translated into appropriate alert limits, defined in terms of

- the absolute level of vibration or of particular vibration features.

- the change in vibration, or particular vibration features from that associated with a known healthy state (i.e., trend monitoring).

Because of the complexity of the vibration generation characteristics of mechanical systems, it is not possible to analytically determine appropriate alert limits for vibration energy levels unless these are simple measurements, such as 1/rev or 2/rev vibration, relating to forces generated by a degree of unbalance or misalignment. The alert limits must be based on relevant measured data. Therefore, the direct and indirect evidence used for CBM credit validation must support the definition of alert limits. In contrast, some defect pattern CIs can be set on a semi-analytical

basis as the defect pattern should be present if a bearing has the related defect, and not present if the bearing is healthy.

A.3.2.3 Appropriate Intervention Action and Associated Monitoring Frequency.

Procedures shall be defined to describe how to interpret the HUMS CI data following an alert and the associated required maintenance actions, which should include checks to verify the correct operation of the HUMS instrumentation prior to performing any on-aircraft intervention actions. There are two possible intervention actions for the OCB

- to inspect the OCBs, which can be performed in situ.
- to remove and replace the bearings, which requires removal of the oil cooler.

Both actions must be performed postflight by maintenance personnel. Therefore, the monitoring frequency must be sufficient to facilitate the gathering of enough evidence during a flight to determine whether there is a requirement for postflight maintenance. This evidence should include information on whether there is any trend in the data during the flight. Therefore, a single data point does not constitute adequate evidence. For a flight of representative duration, the monitoring frequency must be sufficient to allow a minimum of two data points, and ideally three or more, to be gathered.

A.4 VALIDATION METHODOLOGY.

MG-15 states that all HUMS applications should have their validation process based on suitably representative physical data [A-1]. This process may use direct or indirect evidence, or a combination of the two, depending on the credit type and the criticality on the aircraft of any HUMS failure or malfunction.

Since the criticality of the oil cooler CBM credit is deemed to be Class III/Major, the validation methodology can depend on indirect evidence. The following section provides a technical justification for this use of indirect evidence, and considers the factors determining what and how evidence should be used.

A.4.1 TECHNICAL JUSTIFICATION FOR THE USE OF INDIRECT EVIDENCE FOR CREDIT VALIDATION.

Due to prohibitive cost of component testing and excessive wait time for direct in-service experience to accumulate, it would be unfeasible to validate many HUMS CBM credits on the basis of direct evidence alone. However, in many cases, generic relationships can be defined between component faults and the features generated by these faults in monitored signals, such as vibration, means that there is a clear technical justification for using indirect evidence.

This research project relied on the key principle that, for the identified level of criticality of the target CBM credit, indirect evidence can be used for credit validation.

There are two basic factors that must be addressed when considering the use of indirect evidence.

- Bearing failure mechanisms and progression rates
- Bearing fault detection

Each factor is discussed below.

A.4.1.1 Bearing Failure Mechanisms and Progression Rates.

As explained in section A.3.1.1, bearing failure mechanisms can be dependent on the bearing design, function, location, and environment. Clearly, any indirect evidence based on HUMS in-service fault cases or seeded fault rig tests must involve relevant failure mechanisms and associated design and operational characteristics.

As explained in section A.3.1.4, failure progression rates need to be estimated for the bearing that is the subject of the CBM credit and for the failure mechanisms that must be detected. Once the size or extent of a defect that must be detected has been determined from this information, indirect evidence can be used to demonstrate the ability of HUMS to detect this particular defect, irrespective of the failure progression rate.

In summary, the validity of indirect evidence depends on the failure mechanism involved but not necessarily on the failure progression rate.

A.4.1.2 Bearing Fault Detection.

The basic bearing fault detection requirement can be defined in terms of the failure mechanism and the size or extent of the defect that must be detected. As explained in section A.3.2.1, it is possible to determine the qualitative impact of different failure mechanisms on the bearing vibration data being acquired. Because this relationship between defect and monitored vibration signals is defined in qualitative terms, any indirect evidence related to rolling element bearing faults can be considered as potentially relevant for the credit validation of a particular monitoring technique. The actual relevance of any data should then be determined by analyzing variance factors from the qualitative model. In the case of bearing vibration monitoring, the relevant data would include:

1. Details of the bearing type and loading—Consideration needs to be given to details, such as the type of rolling element bearing (e.g., ball or roller), and the relative magnitudes of the radial and axial loading on the bearing, which may have some effect on resulting fault vibration features.

2. Details of the specific HUMS bearing vibration-monitoring technique and resulting CIs—Monitoring techniques can vary, as described in section A.3.2.1. However, in cases which techniques vary, it is still possible to determine equivalence based on the vibration features that are detected.

3. Details of sensor location in relation to the monitored bearing—For different items of indirect evidence, there will be differences in sensor location relative to the monitored

bearing. This should only be an issue for a particular item of indirect evidence, if the sensor is considerably closer to the monitored bearing than it is to the bearing being validated for CBM credit. Normally there should not be an issue if the sensor location for indirect evidence is at the same distance or further away than the specific application being considered.

4. The local environment of the monitored bearing—For vibration monitoring, this is one of the most important considerations. If a bearing is mounted on an external shaft, somewhat remote from other sources of vibration, fault detection is more straightforward than if the bearing is mounted in a gearbox, surrounded by other components generating vibration that could mask bearing fault-related features. It is potentially acceptable to use a fault case relating to a bearing mounted in a gearbox to validate a CBM credit on a bearing mounted on an external shaft, but not vice versa, unless other supporting evidence is available.

5. In cases in which any seeded defect rig test data are used, details of how closely test conditions match actual aircraft conditions are important. The relevance of the evidence will depend on differences in; for example, defects seeding or initiation, loading conditions, damage propagation conditions, and the structural mounting of the bearing and sensor.

Based on the above analysis, it is considered to be technically justifiable to use indirect evidence for credit validation, initially considering the qualitative fault detection capabilities of a particular monitoring technique and then analyzing variances to determine the relevance of a particular item of evidence. However, there will be a need for some direct evidence to correlate with the indirect evidence, even if direct evidence is relatively limited.

A.4.2 INDIRECT EVIDENCE FOR CREDIT VALIDATION.

A review shall be performed of available indirect evidence for credit validation.

A.4.2.1 Existing Bearing Test Rig Evidence.

The existing UH-60 oil cooler rig test data included in section A.4.3.1 can be used as indirect rig test evidence to support the CBM credit validation research.

The previously defined assessment criteria shall be applied (i.e., failure mechanism, monitoring technique, etc.) to identify relevant indirect evidence for CBM credit validation. The evidence shall be classified according to the applicable failure mechanism and the following information documented:

- Bearing details
- Failure mechanism and progression
- Vibration-monitoring technique applied

- Vibration CIs that detected the defect and how the CIs responded to this (e.g., change in level, etc.)
- An estimate of the size or extent of the defect when first detected
- The CI thresholds for reliable detection
- A weighting to indicate the relevance of the evidence to the CBM credit

A.4.2.2 Existing Bearing HUMS Evidence.

The following sources of indirect HUMS evidence shall be used to support the CBM credit validation research:

- HUMS bearing CI data from the oil cooler on the shielded bearings
- HUMS bearing CI data from documented fault cases on various components and aircraft types

For evidence relating to HUMS-detected bearing defects, the same analysis as in the previous section shall be applied.

Relevant HUMS data can also be used to establish the in-service variation in vibration CI values observed from nominally healthy bearings. This will establish the minimum CI threshold levels that can be used, based on an assessment of the resulting false-alarm rate.

A.4.3 DIRECT EVIDENCE FOR CREDIT VALIDATION.

A similar review of the existing direct evidence for credit validation shall be performed. Once all the existing direct and relevant indirect evidence has been acquired, a gap analysis can be performed between this and all the evidence required for credit validation to determine the requirements for the acquisition of additional direct evidence.

A.4.3.1 Existing S-92 OCB Test Rig Evidence.

Existing S-92 oil cooler rig test evidence includes tests conducted for the original certification of the HUMS, and also to support the investigation of a field problem, as listed in table A-2 (which also identifies relevant UH-60 data). An assessment was performed to determine the extent to which these support the CBM credit validation. The Xs indicate if test-generated data could be used for analysis to help understand a failure mode, repeatability, or detectability.

Table A-2. The OCB Rig Experience

Failure Category	Failure Type	Probability (L, M, H)	Criticality	Sentient UH-60 Testing	UH-60 HUMS SAC Test	S-92 BMU Qualification	S-92 Fleet Investigation
Seal problem	Indented	L	Minor	N/A, shielded	N/A, shielded		X
	Cracks and wear	L	Minor	N/A, shielded	N/A, shielded		
Phenolic cage fault	Cracks	L	Minor	N/A, steel	N/A, steel		
	Breaks	L	Major	N/A, steel	N/A, steel		
Failure Category	Failure Type	Probability (L, M, H)	Criticality	Sentient UH-60 Testing	UH-60 HUMS SAC Test	S-92 BMU Qualification	S-92 Fleet Investigation
Raceway fault	Light to medium spalls	M	Minor				
	Light to medium corrosion/pits	M	Minor	X		X	
	Severe corrosion/pits	L	Minor	X			
Balls fault	Dents	L	Minor				
	Light to medium spalls	L	Minor				
	Light to medium corrosion/pits	M	Minor	X		X	
	Severe corrosion/pits	L	Minor				
Grease issue	Contamination/degraded	M	Minor	X	X	X	
	Loss of lubrication/oxidized	L	Major		X		
Repeatability	Build to build			X	X		X
	Point to point						
	Time effect			X			X
	Cooler to cooler				X		X
	Speed variation (100%-108%)					X	
	Misalignment (1.25°)					X	
	Imbalance (30 lb radial)					X	X
Detectability	FWD vs AFT				X		X
	Sensor location				X		

L = Low
M = Medium
H = High

Following the procedure for the indirect evidence, direct evidence shall be classified according to the applicable failure mechanism, and the following information documented:

- Failure mechanism and progression
- Vibration CIs that detected the defect and how the CIs responded (e.g., change in level, etc.)
- An estimate of the size or extent of the defect when first detected
- The CI thresholds for reliable detection

A.4.3.2 Existing S-92 OCB HUMS Evidence.

The majority of the available S-92 OCB HUMS data relate to healthy bearings. However, there are multiple examples of a manufacturing defect.

Further analysis of the existing database of S-92 oil cooler HUMS data is expected to be required to support the CBM credit validation. This may include an investigation of HUMS trends associated with any identified faults and a statistical analysis to identify and investigate any occurrences of high vibration that cannot be related to a fault. The assessment of this data shall be similar to that of the previous section. In addition, the in-service HUMS data shall be used to

- establish the correlation between vibration CI values obtained from the test rig and the on-aircraft HUMS.

- establish the minimum CI threshold levels that can be used in the on-aircraft HUMS, based on an assessment of the resulting false-alarm rate.

A.4.3.3 Gap Analysis.

A gap analysis shall be performed between all the existing indirect and direct evidence and that which is required for credit validation to determine what additional direct evidence (if any) must be acquired.

If all the existing evidence is indirect, a degree of direct evidence for the actual equipment being monitored is still likely to be necessary to prove similarity of application, demonstrate that the applied vibration-monitoring technique is effective on-aircraft, and determine monitoring thresholds.

A.4.3.4 Acquisition Plan for Additional Direct Evidence.

Based on the results of the gap analysis, a plan shall be developed to acquire the additional direct evidence required to validate the proposed CBM credit. As this credit relates to CBM for the S-92 OCBs, it is unfeasible to perform on-aircraft trials introducing abnormal states and measuring effects (in contrast to, for example, a shaft balance measuring function, where it is possible to introduce degrees of imbalance and calibrate the response). Additional direct evidence can be obtained in two ways:

1. Acquiring further in-service experience on HUMS-equipped aircraft. This is a low-cost option, but will delay the introduction of the CBM credit for an indeterminate period.

2. Performing additional rig tests, including seeded defect tests (where a defect is introduced, allowed to develop, and the response verified).

Any rig tests should be representative of the on-aircraft conditions, and it should be established that the evidence gathered from these tests is valid on the aircraft in flight.

A.4.3.4.1 Plan to Acquire Additional Test Rig Evidence.

For the FAA HUMS research program, limited testing on the S-92 OCBs shall be performed to provide additional direct evidence for validation. A two-phase oil cooler test plan was developed to cover the capture of baseline data (Phase 1) and bearing seeded faults (Phase 2). Sufficient data will be gathered to demonstrate and evaluate the validation process, but it is not intended to be all the data that may be required to fully certify the credit.

Phase 1 of the test plan is outlined in table A-3. The focus is on collecting baseline data, LTF data, repeatability effects, and detectability effects. The LTF data includes bearings with light spalling and disassembly-induced cracked cages. The repeatability effects include point-to-point, time effect, and imbalance. The detectability effects include defect location and sensor location.

Table A-3. Phase 1 Oil Cooler Test Plan

Test	Test Duration (hour)	Test Location		Shaft Imbalance*	S-92 OCBs**				
		Oil Cooler Rig	Sentient Rig		Healthy	Field Issue (AC 27)	LTF 2500+	Pulled for High Hours 2500+	Objective
1	1	X			FWD/AFT AC_4J				Baseline
2	1	X		X	FWD/AFT				
3	1	X				FWD/AFT 8841/8844			Detect and characterize bad
4	1	X		X		FWD/AFT 8841/8844			
5	1	X					FWD/AFT 5785/5801		Characterize normal vibrations at 2500 hours that are being pulled due to time, not vibe limits
6	1	X		X			FWD/AFT 5785/5801		
7	1	X						FWD/AFT AC_R	Characterize normal vibrations at 2500 hours that are being pulled due to time, not vibration limits
8	1	X		X				FWD/AFT AC_R	
9	1	X			AFT 5796		FWD 5793 (2 spalls)		-Sensitivity to location -Ability to detect single fault. -Transmission path
10	1	X		X	AFT 5796		FWD 5793 (2 spalls)		
11	1	X			FWD 5796		AFT 5793 (2 spalls)		-Sensitivity to location -Ability to detect single fault. -Transmission path
12	1	X		X	FWD 5796		AFT 5793 (2 spalls)		

*Shaft imbalance created to amplify known vibration issues
**Maintain original face orientation when swapping
AC = Aircraft

Phase 2 of the test plan includes tests for failure progression and failure detection. The failure progression tests include cage break progression and loss of lube progression with medium spalling. The failure detection tests include bearings that have five levels of corrosion and pitting, assembly dent defects, and two levels of bearing spall. The outline is included in table A-4.

Table A-4. Phase 2 Oil Cooler Test Plan

Test	Description	Objective
1	14-point tests with UH-60 bearings installed in S-92 blower. Need to run good sample of bearings that span across 5 levels of corrosion and pitting. Potential set: bearings 08, 11, and 13 had no damage, bearings 14, 15, and 20 had trace damage, bearings 02, 10, and 12 had light damage, bearing 19 had moderate damage, and bearings 05, 06, 21, and 17 had severe damage.	Measure detection horizon for BMU location in S-92 oil cooler. Quantify correlation to UH-60 location.
2	2(a) Create dent on S-92 ball bearings for one bearing specimen. 2(b) Run point test in S-92 blower. 2(c) Repeat with imbalance.	(1) Simulate S-92 manufacturing/assembly issue with dents on balls. (2) Characterize signature. Signature should be similar for spall. (3) Measure affect of radial load on bearing with defect.
3	Using S-92 bearing with cage fracture create break. Run bearing until torque in bearing rig hits limit or 200 hours is reached. Inspect at 100 hours. May modify test if not progressing. Final teardown and inspection.	(1) Characterize cage failure mode. (2) Characterize cage failure progression.
4	4(a) Using bearing with slight spall run point test in S-92 blower. 4(b) Repeat with imbalance. 4(c) In bearing rig increase loads to grow spall to medium size. 4(d) Run point test in S-92 blower. 4(e) Repeat with imbalance.	(1) Characterize light spall signature. (2) Characterize medium spall signature. (3) Characterize imbalance effect.
5	Degrease bearing from test 4. Run bearing until torque in S-92 blower stand hits limit or 200 hours is reached. Inspect at 100 hours. May modify test if not progressing. Final teardown and inspection	(1) Characterize loss of lube failure mode. (2) Characterize loss of lube failure progression.

A.4.3.4.2 Plan to Acquire Additional HUMS Evidence.

In addition to, or as a partial alternative to, the acquisition of additional test rig evidence, a plan may be produced to obtain certain elements of missing evidence for credit validation from future in-service HUMS experience. For example, for a limited time, this may involve tracking particular in-service components, reporting on their condition during maintenance, and correlating this condition with the acquired HUMS data.

A.4.4 DOCUMENTATION FOR CREDIT APPROVAL.

The direct and indirect evidence for credit validation shall be documented for credit approval. This shall include evidence that the required failure modes will be detected using the analysis techniques and alert thresholds specified. If required, any limitations or additional compensating positions shall be specified.

A.5 CONTROLLED INTRODUCTION TO SERVICE.

Vibration measurements can be affected by the structural and dynamic characteristics of monitored systems and by data acquisition conditions. For all HUMS vibration health-monitoring techniques, a plan for a controlled introduction to service is required to fully validate associated CBM credits. This is commonly known as a Controlled Introduction to Service (CIS) plan.

As a minimum, for oil cooler credit validation the CIS plan should include requirements for the following:

1. Application of the HUMS data acquisition conditions and monitoring thresholds specified during the development phase, which is the phase in which developmental work is performed for the target CBM. This may include rig tests or analysis of in-service data to generate the required evidence for credit validation.

2. The collection and review of oil cooler HUMS CI data and alerts from a number of operational aircraft for a minimum specified period, which should be defined in flying hours.

3. The collection of information on all relevant oil cooler maintenance actions, documenting the observed health of the components and any defects found.

4. Correlation of the HUMS CI data and alerts with component condition observed during maintenance to identify false alarms and verify that the expected fault detection capabilities are being achieved.

5. An analysis of the acquired HUMS data to (1) verify that the data are being acquired at the expected frequency and are of the expected quality, (2) identify any unexpected variations in data between aircraft or due to operational factors, and (3) establish the false-alarm rate using the initially defined thresholds.

6. Refinement of monitoring thresholds and/or data acquisitions to address any deficiencies identified in the previous steps, followed by a further evaluation period to demonstrate that the refinements have been effective.

7. Periodic reviews of progress on the CIS phase with the airworthiness authority, followed by a final review to determine satisfactory completion of this CIS phase.

8. Defined criteria for the satisfactory completion of the CIS phase, which should include

   - achievement of the specified requirements for the acquisition of operational experience.

   - demonstration that the effectiveness of the monitoring technique is in accordance with that demonstrated in the development phase.

   - demonstration that effective monitoring thresholds have been established.

- demonstration that none of the target component failure mechanisms have been missed, plus documentation of any failures that have been detected.

For a CBM credit, such as the extension or elimination of the oil cooler TBO, the plan may include a requirement for a phased introduction of the credit. This would be expected to follow established procedures for extending TBOs based on maintenance and reliability data, but include the additional requirement for the correlation of the HUMS data with observed component condition.

A.6 CONTINUED AIRWORTHINESS AND SYNTHESIS OF CREDIT.

A plan for continued airworthiness and synthesis of the credit should be produced to validate the performance of the approved oil cooler CBM credit throughout its service use and to manage the effects of any modifications to the oil cooler or the HUMS. This plan shall include requirements for the following:

1. Recording the HUMS service experience. This does not require the acquisition and storage of relevant HUMS CI data from all in-service aircraft, but should include the acquisition of sufficient data to establish reliable aircraft fleet statistics, and also of data associated with any particular component investigations, detected defects, and/or missed defects.

2. Recording the relevant engineering evidence from rejected components, development testing, seeded testing, etc. The established process should capture information on the observed failure mechanisms of rejected components and their condition at the time of rejection.

3. Synthesis of the HUMS service experience with the relevant engineering evidence to provide continued in-service validation of the HUMS credit and, if necessary, identify requirements for refinements to the HUMS application to improve performance.

4. A review process to assess the impact of any HUMS refinements introduced as a result of the previous step or of any other modifications to the HUMS application or the component and equipment being monitored that may affect the credit validation.

A.7 REFERENCES.

A-1. AC 29-2C MG-15, “Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS).”

APPENDIX B—EXAMPLE CERTIFICATION PLAN

B.1 SCOPE.

This section provides a Certification Plan for the example Sikorsky Aircraft Corporation (SAC) S-92® oil cooler Condition-Based Maintenance (CBM) credit, to eliminate the oil cooler bearing (OCB) time between overhauls (TBO) of 3500 hours and go on-condition (see section B.2 for details). This plan complies with Advisory Circular (AC) 29-2C MG-15 [B-1], but assumes that the Health and Usage Monitoring System (HUMS) is a certified and approved system with software assurance commensurate with credit criticality.

The requirements from MG-15 are that "At a minimum, the certification plan should address the proposed means of compliance to each applicable paragraph of this advisory circular for a given application." [B-1] Section B.3 proposes the means of compliance to each applicable paragraph.

B.2 INTRODUCTION.

The S-92 OCB has had its TBO extended from 2500 to 3500 hours through extensive experience and data accrued via the Lead the Fleet program. It is intended to further extend or eliminate this TBO (i.e., putting the OCB on-condition) by submitting additional data and experience to show that the HUMS can give advanced warning of a failure of the OCB. The current inspection schedule for the oil cooler shall remain unchanged with the exception of the OCB TBO, to ensure that there are additional methods of detecting distress in the OCB. The last line of defense shall remain the Bearing Monitoring System (BMS) temperature, which would give a clear indication of an OCB failure.

The end-to-end system shall remain the same, i.e., from the aircraft sensors to the multifunction display (MFD) on the aircraft, and including the data written onto the onboard card by the onboard data transfer unit (DTU). The ground station shall remain as an additional aid for reviewing previous data, as the data can be reviewed via the onboard MFD.

B.3 COMPLIANCE.

B.3.1 INSTALLATION.

B.3.1.1 Common Requirements.

B.3.1.1.1 Criticality Determination.

The S-92 aircraft certification process has included compliance with newer, more stringent industry and regulatory guidelines. The safety analysis approach was directed at compliance with Title 14 Code of Federal Regulations 29 1309 [B-2], 29 547 [B-3], 29 917 [B-4], and 29 863 [B-5]. The rigorous approach detailed in SAE ARP-4761 [B-6] Safety Assessment process was the general methodology used to demonstrate compliance. As part of this, many extensive high- and low-level analyses were performed. These analyses were part of the certification data provided to the Federal Aviation Administration (FAA) in support of S-92

Type Certification. The aircraft-level Failure Hazard Assessment (FHA) and aircraft-level zonal analysis both ensure that the interaction/boundaries of various aircraft system are considered and addressed. FHAs were also performed for flight critical subsystems to determine the effect/criticality of subsystem failure conditions. Controls or compensating provisions in place to limit the likelihood or severity of identified hazards are also described. Failure Modes and Effects Analysis (FMEA) is performed for critical subsystems, such as the drive train, identified by the FHAs. The FMEA focuses on hardware failure modes, the effects of such failures, the means of detecting such failures, the severity class of such failures, and the compensating provisions within the design to lessen the likelihood or severity of such failures.

The criticality of the types of faults that could arise from the oil cooler fan bearing failure has been assessed in the FMEA documented for the oil cooler fan bearing. This has resulted in a criticality of Class III (Major) for this credit, requiring Level C software.

B.3.1.1.2 Mitigating Actions.

Based on a Class III (Major) credit criticality level, Level C software is required for the onboard software. The S-92 HUMS/BMS has Level B software, exceeding minimum requirements. Thus, no mitigating action is required. If a HUMS being used for the example credit had less than Level C software, then careful consideration of mitigating actions would be required. It is not clear there are any practical mitigating actions, except periodic bearing inspection, that could be applied to allow Level D or E software. If the HUMS had a partitioned system having Level C or higher data acquisition software, then perhaps parallel off-board processing of acquired raw data (e.g., vibration signatures) could be used to independently verify onboard calculation of condition and health indicators with Level D or lower onboard software.

B.3.1.1.3 Performance.

Eliminating the OCB TBO to go on-condition would require the highest level of HUMS performance in detecting all relevant credible failure modes. Fundamental requirements would be to have sufficient sampling rate to capture highest defect frequencies appropriate for the condition indicators used to monitor the failure modes. The OCB condition indicators include the monitoring of vibration energy up to 20 kHz. Periodic data acquisition is required throughout a flight to provide multiple data points. The frequency of data acquisition and processing should address, at a minimum, failure progression rates and the desire to have multiple opportunities to detect a fault before it becomes critical, which also allows data trending. The OCB failure modes being monitored by vibration progress slowly for this lightly loaded bearing and can be detected tens of hours before reaching a critical stage. Thus, the collection and processing of data several times per flight hour may be sufficient. However, the S-92 HUMS/BMS also monitors temperature, which is detectable at the later stages of failure when failure progression rates are much higher. The S-92 HUMS/BMS also monitors the swash plate bearing having much higher criticality. Thus, the S-92 HUMS/BMS collects and processes data at a rate of once per second, which far exceeds the minimum sampling rate required for the OCB.

B.3.1.2 Airborne Equipment Installation.

The qualification of the HUMS equipment, i.e., HUMS processor, sensors, and their installation, was certified as part of the standard equipment of the S-92 and therefore is already covered by the aircraft type certification. Signal independence, ensuring that the acquisition of the HUMS signals do not compromise the level of safety or reliability of functions provided by other equipment as a result of signal sharing therefore has been verified.

B.3.1.2.1 Equipment Installation.

B.3.1.2.1.1 Equipment Qualified as Part of Installation.

All the onboard HUMS hardware, i.e., from sensors to the MFDs, as well as the Personal Computer Memory Card Interface Adaptor (PCMCIA) card and the onboard DTU, has been approved under the aircraft type certificate and meets RTCA/DO-160 [B-7].

B.3.1.2.1.2 Software.

RTCA/DO-178B [B-8] directly relates the required Design Assurance Level for software development to the system criticality level, i.e., Level A for Catastrophic, B for Hazardous, C for Major, D for Minor, and E for No effect. The HUMS software was written to meet RTCA/DO-178B Level B, which exceeds the level required for a credit with a criticality of Major.

B.3.1.2.2 Installation Specific Considerations.

B.3.1.2.2.1 Supply of Electrical Power.

The qualification of the HUMS equipment was certified as part of the standard equipment of the S-92 and is therefore already covered by the aircraft type certification, ensuring compliance.

B.3.1.2.2.2 Electromagnetic Compatibility.

The HUMS was part of the original fit on the S-92; therefore, all the onboard HUMS hardware was approved under the aircraft type certificate, ensuring compliance.

B.3.1.3 Ground-Based Equipment Installation.

For S-92, all data processing and exceedance indications were performed onboard. The ground station was used only for data display, not for data processing. Data at decision points could be verified onboard. Often for other aircraft types, the ground station plays a key role in the data processing and credit determination. The example credit under consideration had Class III (Major) criticality, requiring Level C software, which is not practical for ground-based systems that typically reside on commercial off-the-shelf (COTS) computers. Thus, MG-15 provides guidance regarding the use of COTS ground stations, stating that “Any ground-based processing equipment that consists of commercial hardware and software must have satisfactory service history and an independent means of verifying the results of the processing. The integrity and

accuracy of the ground-based equipment will be verified as detailed in a Controlled Introduction to Service Plan." As all the ground-based equipment is COTS, the following shall apply.

B.3.1.3.1 Independent Verification Means.

The HUMS was part of the original equipment on the S-92; therefore, all the onboard HUMS hardware was approved under the aircraft type certificate. This also included the writing of the data to the PCMCIA card via the DTU.

The HUMS ground support station (GSS) was not considered as part of the end-to-end system when the aircraft was certified. The GSS was considered a tool for data display and trending. HUMS data could also be viewed and checked on the cockpit MFD. The data displayed on the MFD will be used to verify the data downloaded onto the GSS. This satisfies sub-paragraph (5) "Any other independent means of verifying the accuracy/integrity of the equipment including software by a satisfactory comparison to the directed action of the HUMS processed data." [B-1] Data were also transmitted to SAC without alteration and could be verified by SAC. MG-15 indicates that the independent verification means may be discontinued with the certifying authority's agreement to modify the original HUMS approval and this requirement may be removed after significant quantities of the processed data consistently agree with the verifying means.

B.3.1.3.2 Integrity Level Considerations.

Prior to credit approval, the example credit under consideration has Class III (Major) criticality, which requires certification of software and processes, including independent means of verification.

B.3.1.3.3 Ground-Based Equipment Hardware.

The S-92 end-to-end system does not include any ground-based equipment, thus this subparagraph is not applicable.

In a system that does include ground-based equipment, such as data processing, display, and possibly printing equipment or other accessories, it must be shown that all such equipment is compatible with the intended application and software by verifying the functions by an independent means.

B.3.1.3.4 Software.

MG-15 specifies that HUMS specific software in the ground station should be developed to the integrity level required by the system criticality assessment using RTCA/DO-178B as the standard. This system-determined level should be a result of the end-to-end criticality assessment and, in general, the same as the airborne software. Mitigating actions are allowed to reduce the software certification level. It is not clear if MG-15 allows the use of independent means of verification as a mitigating action to reduce the software certification level of HUMS specific ground station software. It is the authors' opinions that MG-15 should be modified to

make this clear and they propose that independent means of verification of HUMS specific software is appropriate and adequate.

B.3.1.3.5 Data Processing.

The processing equipment and software is part of the standard equipment specified for the HUMS and has been proven through the years of operation of the S-92 fleets. This includes the following:

- It has the ability to process the amount of data required.
- It does not introduce errors or provide out-of-specification accuracy for any parameter.
- The speed of processing is not limited by the hardware or software.
- The data processing can be accomplished within a reasonable period.

For the S-92, the end-to-end system does not include any ground support equipment or COTS equipment, it thus cannot interfere with the processing of the data. On systems which do contain COTS equipment running Hazardous/Severe Major or Major criticality applications, it would have to be demonstrated that the data integrity from these applications are protected and can be verified by an impendent means.

B.3.1.3.6 Display and Peripheral Equipment.

The display for the processing equipment is part of the standard equipment specified for HUMS and its compatibility and capability to provide clear usable presentation has been proven through the years of operation of the S-92 fleets.

B.3.1.3.7 Data Communications.

For the S-92 CBM Credit, which has a criticality of Major, the end-to-end system does not require any ground support equipment. The ground station provided with the S-92 aircraft is for data display only and does no additional processing of bearing monitoring data. Bearing monitor exceedances displayed on the ground station can be verified on the aircraft MFD. Proactive screening of data for trends or further substantiation of the root cause of an exceedance can be done by the original equipment manufacturer (OEM) using deep-dive analysis of underlying CIs with expert engineers in the loop to fully understand and verify the data. The resultant data analysis and OEM recommendations were additional information provided as further guidance to be used by the operator to determine the condition of the suspect component.

While the formal end-to-end process is confined to the onboard system, data integrity as it is transferred to the ground station and then to the OEM is ensured using traditional information technology methods. Data transfer to the OEM is automated and employs automated data integrity checks, such as check sum error detection and correction. The idea of check sum is to compute a hash function of the data, include the result in the transmission, and ensure that the check sum relations hold at the receiving end through application of standard algorithms. Note that check sums only ensure against accidental data corruption and not corruption caused by malicious attacks. The risk of malicious attacks is mitigated by operator processes used to

control access to the data card and GSS. It can be further mitigated through the application of data quality checks by the OEM. It should be noted that the malicious corruption of data that could withstand such checks, even if data card and GSS access is not controlled, is not plausible because of the highly proprietary and binary data structure used to write the data file in the onboard system.

The GSS downloads the recorded memory unit download (MUD) files from the DTU and condenses them into a more efficient raw data file (RDF) format. No significant data processing takes place on the GSS; it is for display purposes only. Every packet in a MUD or RDF is wrapped in a 32-bit cyclic redundancy check (CRC) word. Anytime the GSS reads those packets, it verifies the CRC to ensure the data matches what was written by the onboard system. The CRC data are in both the MUD and RDF file formats for use in verifying data integrity at any point along the data management chain. The binary format makes it very difficult to intentionally modify that data. Both inadvertent and malicious data corruption would be detected and the affected packet data would be rejected upon download or reprocessing by the OEM. The detection of this would be via messages in the download log file. Prior to any analysis, a final mitigating action to ensure data integrity are automated data integrity and quality checks performed to flag suspect data for OEM engineering expert assessment.

B.3.2 CREDIT VALIDATION.

Compliance to all the sub-paragraphs of paragraph g for the S-92 OCB CBM credit is addressed in the CBM credit validation plan (see appendix A). The plan addresses the following list of topics:

- Description of application and associated credit (section A.2)
- Understanding of the physics involved (section A.3)
- Validation methodology (section A.4)
- Introduction to service (section A.5)
- Continued airworthiness (synthesis) (section A.6)

B.3.3 INSTRUCTIONS FOR CONTINUED AIRWORTHINESS AND OTHER REQUIREMENTS FOR HUMS.

The HUMS was part of the original fit on the S-92; therefore, all the onboard HUMS hardware was approved under the aircraft type certificate.

B.3.3.1 Instructions for Continued Airworthiness.

B.3.3.1.1 The HUMS Instructions for Continued Airworthiness Items.

The onboard HUMS was part of the original fit on the S-92; therefore, the following has already been addressed during the aircraft type certificate approval.

- Control and operating instructions for the HUMS, as used by the flight crew, are contained in the aircraft operating manual.

- The acceptance and rejection criteria and associated actions are included in the aircraft maintenance manual.

- The procedure for when the HUMS is inoperative requires replacement within 10 calendar days corresponding to approximately 25-80 flight hours for normal to heavy usage. This would likely need to be reduced if the OCB TBO was completely eliminated.

- Since HUMS data can be viewed on the onboard MFD, no provisions are required for data transfer when the aircraft is away from the main HUMS data processing base.

- An independent means of ground station processing is not required since HUMS/BMS results are viewable onboard. However, onboard data can be used to verify ground station data displays.

- No mitigating actions are specified for the example credit beyond the existing periodic oil cooler inspections.

- Instructions for CIS.

- A HUMS manual is also provided to expand on the aircraft operating manual used by the maintenance crew.

- Training in the use of the onboard system and ground station HUMS is provided by SAC for customer personnel.

B.3.3.1.2 Ground-Based System and Equipment.

If the ground-based system is part of the end-to-end process for CBM credit determination, the operator should develop a procedure to ensure the security of the ground-based system and equipment and the integrity of the HUMS data. Appropriate measures are well documented in ADS-79B, Appendix E [B-9]. Highlights are provided here.

For the example Class III (Major) credit or others of similar or higher criticality, security measures and procedures should be implemented to prevent the willful, malicious destruction of HUMS data. These measures should include the implementation of both physical security and logical security. Physical security should provide for physical placement of the data storage system in a secure area where only authorized administrators have access. Logical security should be provided in the form of user passwords or other authentication for data access. Logical security should offer the ability of implementing a layered security, allowing different levels of access, including the ability to change or delete data, by different users. Other data integrity methods of securing data should include a strategic plan for backups. Standard guidelines should be developed regarding how data will be stored, who has permission to access, and what modifications are permissible.

B.3.3.2 Owner's/Operator's HUMS Program.

B.3.3.2.1 General.

The changes required as a result of the OCB going on-condition are addressed in the ensuing paragraphs. All other maintenance inspections, overhaul requirements, and life limits for the OCB will remain the same.

B.3.3.2.2 The HUMS Program Items.

The operator must provide a maintenance management information system for tracking the HUMS-monitored component/system, including identification of component/system, recording requirement, tracking procedure, and other related activities. The historical HUMS data must be traceable when such components or assemblies are transferred between aircraft. A procedure for adjusting maintenance credits should be developed by the operator's organization with clearly defined responsibilities to collect, analyze, and act upon the HUMS data.

B.3.3.2.3 Ground-Based System and Equipment.

Since there are no ground-based systems or equipment for the S-92, there is no need for troubleshooting and test procedures of the ground-based HUMS. Similarly, there is no minimum equipment list for the ground-based HUMS.

B.3.3.2.4 Master Minimum Equipment List/Minimum Equipment List.

See section B.3.3.1.1.

B.3.4 REFERENCES.

B-1. AC 29-2C MG-15, "Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS)."

B-2. Title 14 CFR 29.1309, "Equipment, Systems, and Installation," September 17, 2012.

B-3. Title 14 CFR 29.547, "Main and Tail Rotor Structure," September 17, 2012.

B-4. Title 14 CFR 29.917, "Design," September 17, 2012.

B-5. Title 14 CFR 29.863, "Flammable Fluid Fire Protection," September 17, 2012.

B-6. SAE, International ARP 4761, "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment," December 1, 1996.

B-7. RTCA DO-160/ED-14, "Environmental Conditions and Test Procedures for Airborne Equipment," 2010.

B-8. RTCA DO-178B, “Software Considerations in Airborne Systems and Equipment Certification,” 2001.

B-9. ADS-79B-HDBK, “Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for US Army Aircraft,” February 17, 2009.

APPENDIX C—CONTROLLED INTRODUCTION TO SERVICE PLAN

C.1 SCOPE.

This section provides a Controlled Introduction to Service (CIS) plan for the S-92 oil cooler bearing (OCB) Condition-Based Maintenance (CBM) credit, described in the previous sections. This plan complies with Advisory Circular (AC) 29-2C MG-15 [C-1], but assumes that the Health and Usage Monitoring System (HUMS) is a certified and approved system.

The requirements from MG-15 are as follows:

- For many HUMS techniques, a CIS plan may be necessary to fully validate the credit.
- The certification process must include provisions to instruct the continued airworthiness effort to ensure compliance to the CIS plan, see section C.3.
- Data must be accumulated by operational aircraft during the implementation of the CIS to enable refinements and adjustments to the initial criteria. "This period may also allow a proposed credit to be operated in parallel with alternative or standard procedures when it is necessary to gain additional in-service validation by way of back-to-back comparison." [C-1]
- "The plan should include procedures and provisions for this controlled period and should include clear goals by which progress and ultimate termination of this phase can be measured. The plan may include a multi-credit HUMS that will require a phased introduction of credits." [C-1]

C.2 CONTROLLED INTRODUCTION TO SERVICE PLAN.

The aim of the CIS is to perform final validation of the CBM end-to-end system and process to ensure they are adequate for maintaining airworthiness and baseline reliability. The following elements are proposed for the OCB CBM credit:

- Verify that the bearing monitoring system (BMS) data are consistently transferred to the ground support system (GSS) and match onboard data.
- Closely monitor the BMS trends of bearings that have passed the current 3500 hours time between overhauls (TBO).
- Continue routine visual inspections on oil cooler fan.
- Collect HUMS data to ensure normal trends continue and readjust thresholds, if necessary.
- Conduct teardown analysis of any oil coolers having abnormal visual findings and for at least two lead the fleet (LTF), high-hour oil coolers as they reach 500-hour increments from the old TBO.

- Record all maintenance actions and teardown analyses on oil cooler fan to ensure no missed alerts.

- Assess HUMS and credit performance with respect to CIS plan exit criteria

C.3 THE CIS ACTIVITIES.

C.3.1 VERIFY BMS DATA TRANSFER.

Although it is not required, if HUMS data for the OCB CBM credit is closely monitored on the aircraft display, it is desired that the operator ultimately have the convenience of using the GSS to display and monitor OCB data. The following BMS data verification steps shall be performed 20 times, preferably on more than one aircraft (if available), during the first month of the CIS. A minimum of three verifications shall be performed on each aircraft. Each verification shall be performed on a separate operation.

1. After a flight, select the Parameters page on the HUMS multifunction display (MFD) menu and view the BMS trend. Make a note of the time and BMS value of both vibration and temperature indicators at two points on the trend, a peak and a trough value may make it easier to find and test a range of values. Note whether BMS exceedances are indicated.

2. Perform a Crew Change from the HUMS main menu to terminate the current operation and remove the data card.

3. Process the data card on the GSS and verify that the operation just flown has been loaded into the GSS.

4. View the BMS data for the operation just flown and compare that the times and values for the two data points noted in step 1 are the same.

5. Ensure that GSS report of exceedances matches the MFD display.

6. Repeat steps 1 through 4 at least 20 times, satisfying the minimum number of aircraft and the minimum number of verifications per aircraft criteria.

C.3.2 Trend Monitoring.

The BMS trend on any aircraft that has an oil cooler with more than the current 3500-hour TBO shall be closely monitored. The trend shall be checked at least every 50 hours for anomalous trends, i.e., any continually rising trends or step changes in nominal data.

The detection of sustained anomalous trends (~20 to 25 hours) shall result in a visual inspection before the next flight. Anomalous findings from the visual inspection (e.g., purged grease, corrosion, or unusual shaft/fan play) shall result in component removal and a teardown analysis. If no bearing distress is evident during the inspection, operation can continue with close

monitoring of HUMS data. Anomalous trends shall be checked every 25 hours and the time between the routine visual inspections halved until the trend stabilizes.
Any exceedances will be handled according to the standard operating and maintenance procedures. For example, the aircraft can continue to fly for 25 hours after a vibration level-1 (vib-1) exceedance. A vib-2 exceedance causes the aircraft to be grounded until appropriate maintenance actions are taken, starting with a visual inspection. In the case of a sporadic exceedance with no visual finding, data will be monitored and a visual inspection conducted after each flight until the sporadic exceedances disappear. A sustained vib-2 exceedance shall result in component removal and a teardown analysis.

C.3.3 ROUTINE VISUAL INSPECTIONS.

Normal routine visual inspections of the oil cooler shall be performed every 50 hours, per the standard maintenance manual, to check the health of the oil cooler and bearings. Distress in the bearings will normally result in an excessive amount of purged grease, corrosion, and/or excessive play in the shaft/fan found during visual inspection. This shall result in component removal and a teardown analysis.

C.3.4 TEARDOWN ASSESSMENTS.

For any oil cooler showing any abnormal findings during routine inspections shall result in component removal and a teardown analysis. If no bearing distress is evident during the inspection, operation can continue with close monitoring of HUMS data.

Teardown analyses of at least two LTF aircraft that have high-hour oil coolers shall be performed as they reach 500-hour increments from the current TBO; i.e., at 4000, 4500, 5000 hours, etc.

C.3.5 RECORDING OF MAINTENANCE ACTIONS AND TEARDOWN ANALYSES.

An accurate log of all maintenance actions and teardown analyses performed on the oil cooler shall be maintained and submitted, with the teardown analyses, at the end of the CIS period as proof that there were no missed alerts by the HUMS.

C.4 THE CIS ASSESSMENT.

Assess HUMS and credit performance with respect to CIS plan exit criteria.

The nominal period of CIS should last until the following minimum requirements are met for the example Class III (Major) OCB TBO extension credit.

1. If the TBO is extended, but not eliminated, two oil coolers have successfully reached the new TBO.

2. Sufficient data are collected to validate HUMS performance metrics, e.g., probability of detection (POD) and Probability of false alerts (Pfa), per following the minimum requirements. If HUMS metrics have already been established through seeded fault

testing, field experience, or previous CBM credit validations, additional validation only needs to confirm HUMS findings from at least five teardown analyses (regardless of whether faults are present) and satisfaction of Pfa metric during the course of the CIS. If additional data are required to validate the POD, validation of at least three positive HUMS indications are required from combination of seeded fault tests, previous field experience, or CIS findings while satisfying Pfa requirements. The number of findings required may be higher for higher-criticality credits.

If Pfa performance does not meet requirements or false negatives are found during visual inspections or TDAs, thresholds should be reevaluated. The CIS should continue until HUMS performance metrics are validated with the new thresholds. If HUMS performance cannot be achieved, then CIS should be terminated and the CBM credit rescinded.

C.5 REFERENCE.

C-1. AC 29-2C MG-15, "Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS)."

APPENDIX D—CERTIFICATION AND TECHNOLOGY TRANSFER PLAN

D.1 SCOPE.

For the Condition-Based Maintenance (CBM) credit to be successfully implemented all the requirements of Advisory Circular (AC) 29-2C MG-15 need to be satisfied. This starts with defining the end-to-end system and then the criticality of the CBM credit being sought. The four main components of MG-15, i.e., installation, data acquisition, credit validation, and continuing airworthiness, then have to be addressed to ensure compliance with the AC. Compliance to these four components for the Sikorsky S-92® oil cooler bearing (OCB) is detailed in the Example Certification Plan (see appendix B).

Information is also required by the operator to enable them to continue to operate the aircraft in an efficient and safe manner; this is normally in the form of Instructions for Continued Airworthiness (ICA).

D.2 INSTRUCTIONS FOR CONTINUED AIRWORTHINESS.

For the S-92, most of the ICA requirements have been satisfied during the aircraft certification process, as the Health and Usage Monitoring System (HUMS) was already an integral part of the aircraft that was certified. Compliance to MG-15 is detailed in appendix B.3.3. The additional instructions associated with this credit would need to be incorporated in the Aircraft Maintenance Manual, (AMM)/Airworthiness Limitations, and HUMS manuals.

These additional instructions would detail the change in maintenance schedule of the OCB, by the removal of any action related to the 3500-hour time between overhauls. All other current scheduled inspections shall remain in place, which would work as a backup to the HUMS to ensure that no faults are missed.

The recording of HUMS alerts, maintenance actions, and teardown analyses related to the OCB shall continue after the controlled introduction to service to enable fleet statistics to be monitored. This will ensure that defects are being detected by the HUMS and that none are being missed. The review of the fleet data may also result in the alert threshold being revised based on the fleet experience.

D.3 REFERENCES.

D-1. AC 29-2C MG-15, “Airworthiness Approval of Rotorcraft Health and Usage Monitoring Systems (HUMS).”