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14. ABSTRACT
Machinery diagnostics and prognostics is an enabling technology for preventing equipment operational failures, reducing maintenance costs and improving system design. The Navy is currently investigating the impact of this technology for shipboard applications. A research team is currently participating in a shipboard demonstration of machinery monitoring system for a ships service gas turbine generator (SSGTG) set. The monitoring equipment was developed using modified commercial-off-the-shelf (COTS) technology to enable rapid revisions to the software as design requirements changed, with an open architecture to enable monitoring multiple components. A key focus of this study concerned the condition of the bearings and gears of the mechanical components as well as the electrical components such as windings and diodes.

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FINAL REPORT FOR

Accelerated Capabilities Initiative Condition-Based Maintenance: Machinery Diagnostics/Prognostics II

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Gas Turbine Condition-Based Maintenance

ARL Focus on Oil Monitoring and Analysis

ACI Architecture, Algorithms, and Hardware

Condition-Based Maintenance / ACI RCM Workshop

Workshop on Maintenance and Diagnostic Requirements for AGT-9140
Gas Turbine Generator Set

Accelerated Capabilities Initiative in Machinery Diagnostics and Prognostics II
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Future Naval Capabilities – Applications and Implementation

Final Report

"SHIPBOARD DEMONSTRATION OF A MACHINERY MONITORING SYSTEM"

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Abstract: Machinery diagnostics and prognostics is an enabling technology for preventing equipment operational failures, reducing maintenance costs and improving system design. The Navy is currently investigating the impact of this technology for shipboard applications. A research team is currently participating in a shipboard demonstration of machinery monitoring system for a ships service gas turbine generator (SSGTG) set. The monitoring equipment was developed using modified commercial-off-the-shelf (COTS) technology to enable rapid revisions to the software as design requirements changed, with an open architecture to enable monitoring multiple components. A key focus of this study concerned the condition of the bearings and gears of the mechanical components as well as the electrical components such as windings and diodes.

Key Words: Health Monitoring System; Integrated Component Health Monitor; Ship Service Gas Turbine Generator; System Health Monitor

Introduction: The Pennsylvania State University Applied Research Laboratory (ARL) is currently performing an Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics (ACI), sponsored by the Office of Naval Research in the areas of reliability-centered maintenance, instrumentation, and machinery diagnostics and prognostics. Machinery diagnostics and prognostics is an enabling technology for preventing equipment operational failures, reducing maintenance costs, and improving system design. The Navy is currently investigating the potential of this technology for shipboard applications. A research team consisting of The Office of Naval Research, Naval Surface Warfare Center Carderock Division - Philadelphia, ARL, Renssalaer Polytechnic Institute, University of Kentucky, Oceana Sensor Technologies (OST), Rolls-Royce Allison, and RLW, are currently participating in a shipboard demonstration of a machinery health monitoring system (HMS) for ships service gas turbine generator (SSGTG) sets. Specific components for the SSGTG were selected based on a study conducted by ARL and the Navy including life cycle managers, design engineers, sailors, and port engineers along side both the Pacific and Atlantic fleet's technical services engineers [1].

The goal of the ACI was to develop a hierarchical architecture to implement machinery monitoring at the machine, component and system levels. The ACI demonstrated the architecture at the intelligent node (wireless technology), system and platform level. Most of the hardware and software development however, focused on the intelligent node level. The intelligent node enables machinery health monitoring of particular machinery components. The purpose of the machinery Health Monitoring System (HMS) was to

obtain as much data and information at the component level as possible, and to transmit potential alert and alarm messages to the ship's crew onto a display station.
An important task for transition of the ACI technology was to acquire realistic data to validate the algorithms and hardware/software for fleet implementation. For transition, emphasis was placed on validation of the ACI-developed hardware and software. The validation phase focused on data acquisition at the Philadelphia Land Based Engineering Site (LBES), algorithm validation on test rigs, testing on the electrical generator, and accessory gearbox rigs to provide fusion of vibration data with electrical subsystems. The ACI concluded with a shipboard demonstration of the developed technology. This included developing appropriate technical specifications, obtaining approval and support from equipment owners, and implementing the technology based on ship availability.

A study [1] based on reliability-centered maintenance principles produced a number of components to instrument. In particular, many of the signals that were originally identified as monitoring applications are actually included in the control system. Of the original areas selected, only the generator (electrical and mechanical systems), the reduction gearbox and the accessory gearbox, remained as candidates for using intelligent nodes. (See Figure 1)

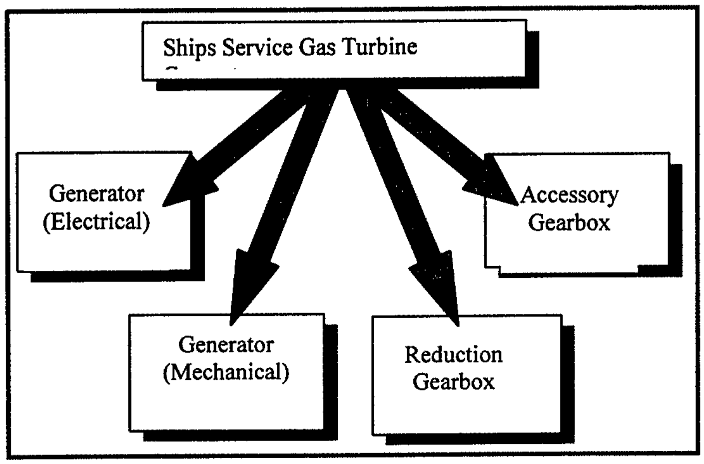

Figure 1. SSGTG Monitored Components

Health Monitoring System: The machinery health monitoring system is shown in Figure 2 and employs a data fusion capability [2]. Data is processed and fused at both the ICHM and SHM level. At the ICHM level, sensor data is first converted to engineering units, then processed using filtering, FFTs, wavelets or other techniques to enhance the signal to noise ratio and to extract signal features indicative of component health. After initial processing, thresholding or other techniques are used to determine whether the sensor indicate the onset or progression of damage. Kalman filters are used to smooth the data and predict the future values of the features.

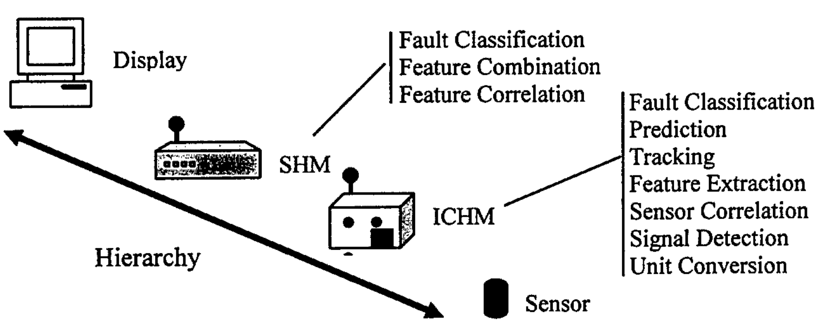

Figure 2. Machinery Health Monitoring System – Data Processing and Fusion

At the SHM level, features from multiple ICHMs can be correlated and combined, then input to fault classification algorithms. In some cases, different ICHMs may have redundant sensors whose data can be correlated to improve the reliability of the measurements and detect sensor problems. The machinery health monitoring system includes some ICHMs that may provide overlapping information at the same ICHM level – for example, each of the four accelerometers mounted on the reduction gearbox will measure (to some extent) the same vibration signals. The machinery health monitoring system can also employ fuzzy-logic to classify machinery fault conditions.

The machinery HMS was completely installed on the *USS Fitzgerald* (DDG-62), an *Arleigh Burke* class guided missile destroyer home ported in San Diego California. The *USS Fitzgerald* is a guided missile destroyer, commissioned in 1995 and is homeport in San Diego, California. There are three Allison 501-K34 SSGTGs; on board that supply electrical power to the ship. During normal steaming, two of the turbines are kept operational with the third standing by as backup.

The components of the machinery HMS installed on the *USS Fitzgerald*, are shown in Figure 3, and consist of:

- 4 ARL intelligent component health monitoring systems (ARL-ICHM)
- 1 ICHM.20/20 and Dongle developed by OST (hardware) and RLW (software)
- 1 ARL System Health Monitoring system (SHM)
- 1 ARL designed power supply unit

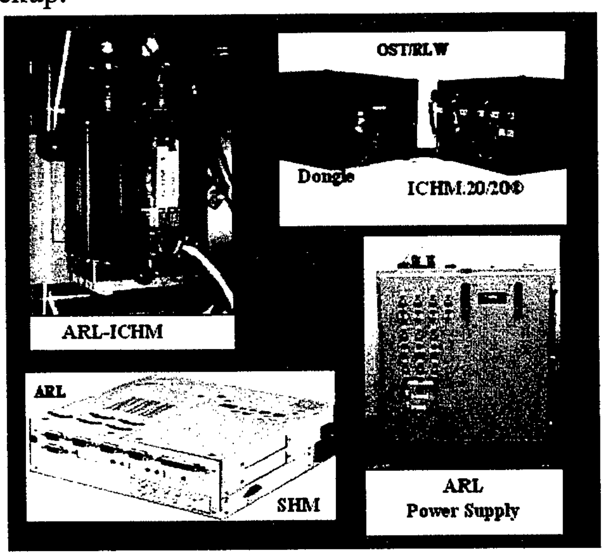

Figure 3. Health Monitoring System

The lowest levels of the ACI hierarchical architecture for machinery health monitoring system are the ICHMs. The ICHM collects data from the sensors and performs calculations on the data to provide an indication of the component health to the SHM. Each of the four rugged PC-104 based ARL Integrated Component Health Monitors (ICHMs) utilizes a Proxim radio operating at a carrier frequency of 2.4 GHz, and is fabricated by integrating commercially available components (such as CPU and analog to digital converter boards), with an ARL-designed signal conditioning board. The custom signal conditioning board provides power to ICP™ accelerometers, anti-alias filtering for acceleration and temperature measurements and permits monitoring sensor bias voltages for an indication of sensor health. Each ARL-ICHM is capable of collecting five channels of data at a maximum aggregate sampling rate of 200 kHz from the measured components, performing calculations, and running algorithms on the data to provide an indication of the component health to the system health monitor. It also has the capability of being field programmable to permit upgrades to data analysis and other functions. A watchdog was incorporated into the design to allow the system to restart in the event of a power loss. A metal container using military specified connectors for data acquisition and power houses the internal components. More specifically, the functions of the ICHM include:

- Data acquisition
  - Data acquisition from temperature and vibration sensors
  - Signal conditions (e.g., sensor power, filtering, amplification)
  - Data conversion (multiplexing, A/D conversion)
  - Generated test and calibration signals
  - Data analysis with alert and alarm messages
- System support
  - Controls communication, data acquisition, data analysis, system clock
  - Windows NT
  - ICHM self-diagnostics, watchdog timer control
  - Physical interfaces (keyboard, video, mouse and com ports.)

The OST/RLW ICHM.20/20 utilizes 2.4 GHz Bluetooth™ wireless technology, while processing data on a Sharc DSP. This unit has one high-resolution channel (24-bit, AC-coupled, sample rate 4-48 kHz), and one low-resolution channel (12 bit, DC-coupled, analog input, sampling under software control). The shipboard designed ICHM.20/20 wirelessly passes data and receives information queries from the System Health Monitor (SHM) via a Dongle, which is RS-232 serial ported into the SHM.

The SHM receives input from multiple ICHM units to reduce false alarms and to improve the reliability of the alert and alarm information being supplied to the crew via a display station. The SHM also stores the raw data from the ICHM units for future data analysis. The SHM includes:

- System hardware
  - 233 MHz Pentium processor
  - 156 megs of RAM
  - NT4 operating system
  - Proxim radio
  - Keyboard, video, mouse and com port interfaces

A stand-alone power supply unit was designed and developed by ARL, to ensure delivery of proper power levels to the ICHM's and to the SHM. This power supply unit also has a thirty-minute battery backup in the event that the ship should lose power.

ICHM Monitoring Capabilities: Figure 4 shows the top-level view of the system. Overall system health and status are derived from the health and status of the functional subsystems, which comprise the system. For the purpose of the ACI demonstration, the gas turbine generator is broken down into four subsystems: the generator, the reduction gearbox, the accessory gearbox, and the engine. The engine includes the compressor and the turbine.

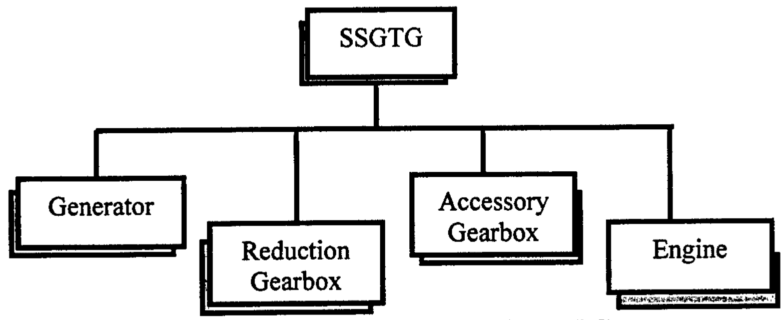

Figure 4. Overview of Monitored Systems

The 501K-34 generator used in the SSGTG can be subdivided into two types of components, (electrical and mechanical) and is monitored by two separate ICHMs, see Figure 5. ICHM 1 monitors the electrical components of the generator, which include the stator windings, field windings, and the rectifier diode used in the exciter circuit. This is accomplished by measuring each phase of the output voltages and currents along with the exciter current and voltage. To ensure the health of the ICHM, internal temperature is also measured. ICHM 2 monitors both the vibration and temperature levels on both the drive-end and the permanent magnet assembly (PMA) end of the generator, with two accelerometers/temperature sensors placed 90 degrees apart on each end. The bearings associated with the generator are journal bearings, and although accelerometers would not be a likely candidate to measure the health of these bearings, it was decided that in the event of a catastrophic bearing failure or an electrical failure, monitoring the effects of one component on the other could be beneficial in evaluating the health of the

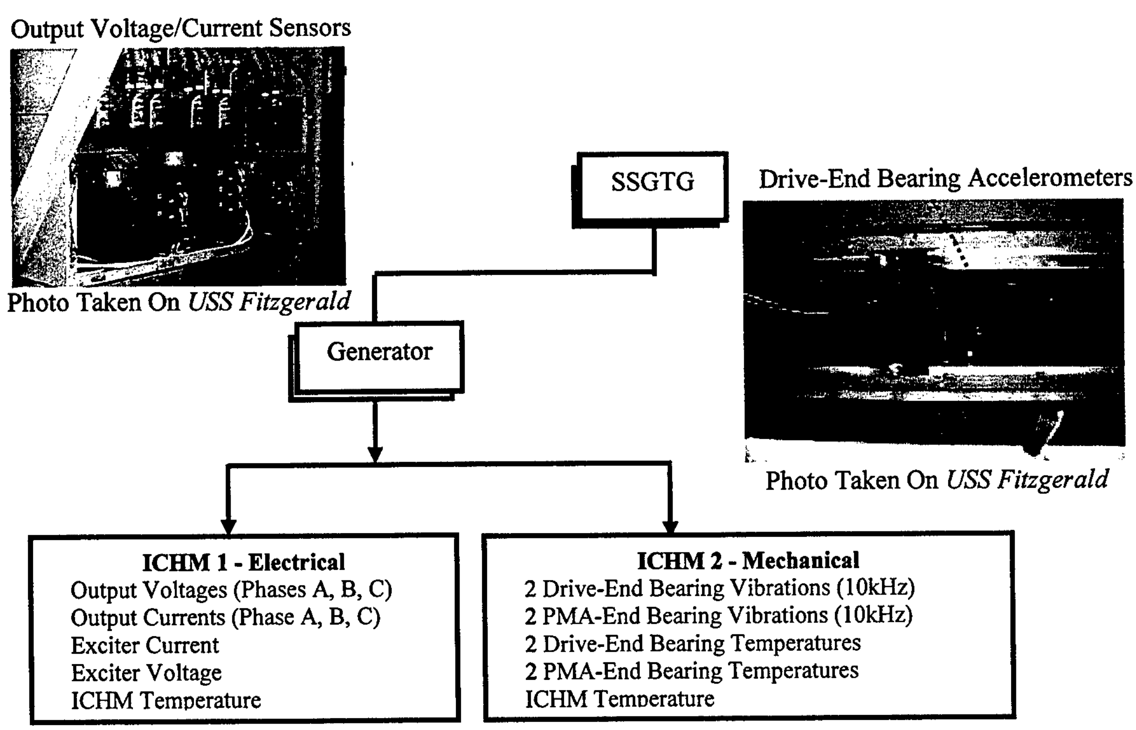

Figure 5. Generator Data Collected From ICHMs 1&2

generator. Bearing temperatures are also being measured to track the temperature of both the bearings. Both ICHMs are mounted outside of the gas turbine engine module in the engine compartment, and therefore are only subjected to the temperature ranges in the engine compartment.

Shown in Figure 6, the reduction gearbox is monitored by ICHM 3 which is mounted inside of the gas turbine engine module and which is subjected to the temperatures of that environment. Because of the possibility of the compartment reaching temperatures near the critical operating temperature of the ICHM, internal ICHM temperatures are continuously monitored. The reduction gearbox consists of a high-speed shaft and pinion that drives a low-speed shaft and gear assembly that drives the generator. Four accelerometer/temperature sensors are used to measure both vibration and temperature for each of the following components: the high-speed shaft and pinion, the high-speed non-drive-end shaft, the low-speed shaft and gear, and the low-speed non-drive-end shaft. This configuration allows data to be collected not only to determine the health of the gears, but also to aid in the understanding of how failure from either the generator or the engine can affect the reduction gearbox.

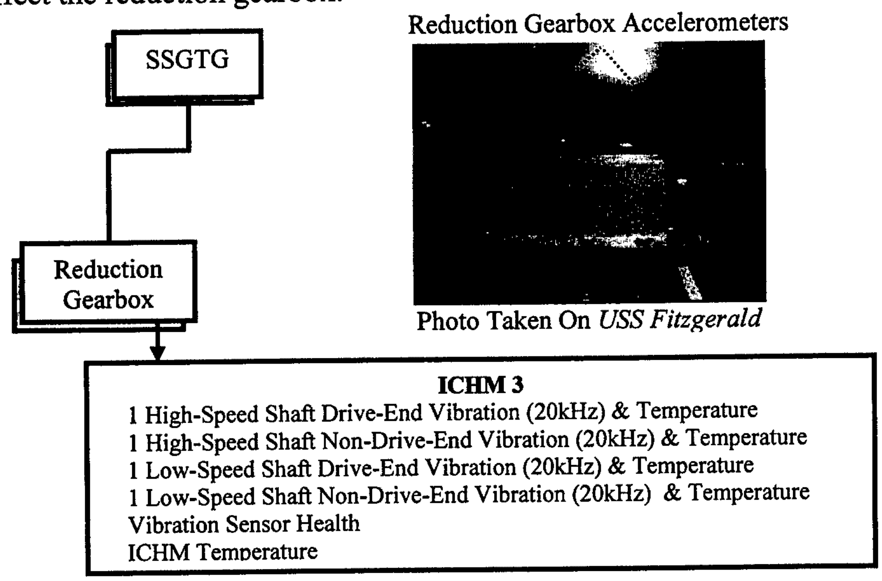

Figure 6. Reduction Gearbox Data Collected From ICHM 3

ICHM 4 is mounted inside the gas turbine engine module and therefore like ICHM 3 is exposed to higher engine temperature and is also continuously monitored. As seen in Figure 6, one accelerometer/ temperature sensor is mounted on the top of the inlet housing to monitor the compressor bearings and shaft vibrations along with the compressor surface temperature. The accessory gearbox has a triaxial accelerometer mounted on its midsection on the underside. The accessory gearbox is a complex component that controls the fuel pump, oil pumps, possible tachometer, and governor. Although this gearbox provides a challenge for data processing, it is essential since the Navy is currently investigating extending its life.

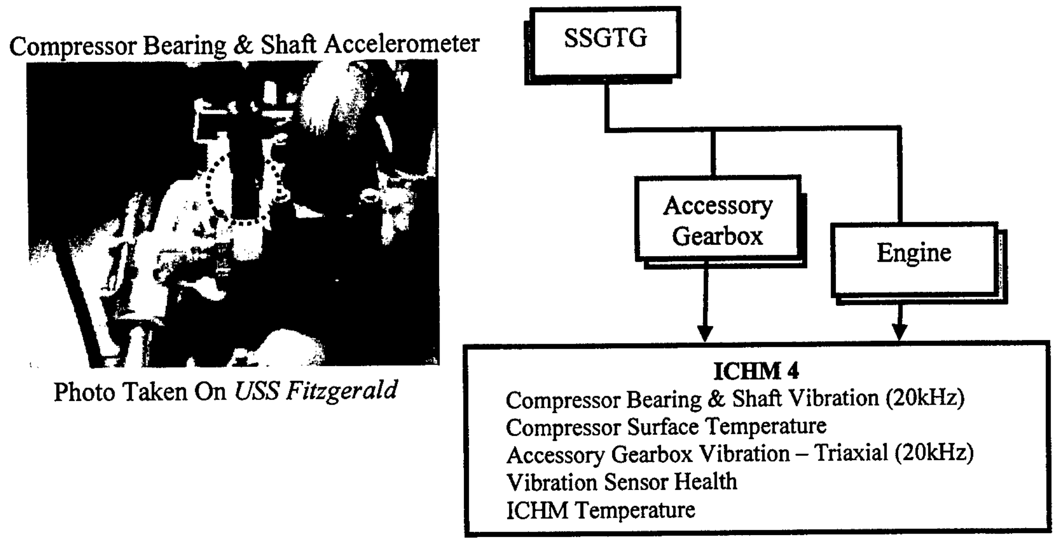

Figure 7. Accessory Gearbox & Engine Data Collected From ICHM 4

Preliminary Data Findings: A 5KW scale model of the 501-K34 has been designed and delivered to ARL, by the University of Kentucky, providing a means to simulate the generator onboard a ship with, either or both, mechanical and electrical faults. In addition, a high-speed accessory gearbox rig is currently under construction to assist in initial tests of the intelligent component health monitors and to accurately determine the characteristic frequencies of the gearbox under loading conditions. Data were also collected at the LBES on both the K17 and K34 SSGTGs during an integrity test of the HMS, which was necessary for the approval process to gain access to a US Naval ship. The K17 was similarly instrumented and monitored under the Reduced Ships-Crew by Virtual Presence (RSVP) program [2] sponsored by Jim Gagoric, ONR Code 334 on the *USS Monterey* (CG-61) in February 2001.

Data collected on test rigs, at the LBES, and on the previous ship install enabled the determination of operating values for the generator voltages and currents, including ranges for the various accelerometers on the accessory and reduction gearboxes. Table 1

Table 1. Monitored Components and Data Sources

	USS Monterey K17 Underway	NSWCCD LBES K17	USS Fitzgerald K34 Underway	NSWCCD LBES K34	PSU/ARL Generator Test Rig	NSWCCD Allison 501K Seeded Faults	PSU/ARL High Speed AGB Test Rig
Generator Electric	Yes	Yes	First Qtr 2002	Yes	Yes 07/23/01	—	—
Generator Mechanical	Yes	Yes	First Qtr 2002	Yes	Yes 07/23/01	—	—
Reduction Gearbox Mechanical	Yes	Yes	First Qtr 2002	Yes	—	—	—
Accessory Gearbox/Engine Mechanical	Yes	Yes	First Qtr 2002	Yes	—	Yes Only AGB	Under Construction

shows the relationship between the components monitored and the various data collection sources. This data also provided frequency spectra to support algorithm development for installation on the *USS Fitzgerald* (DDG-62).

As an example when looking at a feature comparison from the LBES 17 data vs. the Monterey K17 underway data on the reduction gearbox, similarities were found under identical load and power factor conditions. The Crest Factor feature for the LBES fits very well within statistics, as seen in Figure 8.

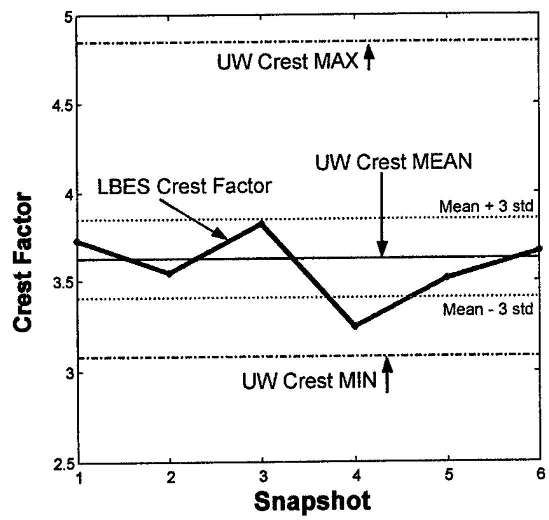

Figure 8. Crest Factor on Reduction Gearbox (Comparison)

Similar results were found for other feature comparisons. Table 2 depicts which LBES feature data means are within 1-3 standard deviations of the underway feature data means, when using the same preprocessing parameters and techniques. Several features do not behave similarly and require further investigation.

Table 2. LBES K17 Features vs. Monterey K17 Underway Statistics

	Ch#	RMS	Skew	Crest	Kurt	EnvKurt	EnvPk	EnvFrq	DemPk	FM0	SLF	S01	S02	M6A	M8A	FM4
Elect. Generator	1															
	2															
	3															
	4															
Mech. Generator	1	1		3			1	1	3	1	3		1	1	1	1
	2	3		3	3	3	3	1	3	3		1	1	1	1	1
	3			3	1		3			3	3	1	1	1	1	1
	4		1			3	3	1		3	3	3	1	3	3	3
Reduction Gearbox	1			3	3	3	3								3	
	2		3	3		3	3		1						3	
	3			1			3	1	3	1	1					
	4	1	3	3			3	3	3				3		3	
Eng	1	3		1	3											
Acces. Gearbox	2			3	3											
	3															
	4			3												

The key result is the similarity of the features calculated on LBES and shipboard data, and indicates the value of the Philadelphia LBES test facility in refining the algorithms necessary for shipboard applications.

Conclusions: The effort described in this paper illustrates the technical challenges involved in performing an actual demonstration of condition monitoring for a shipboard application. During each phase of the effort, from development of the intelligent nodes, selection of the components to be monitored, preliminary tests and shipboard installation valuable lessons were learned. For example, during the study some components that were not recommended to be monitored, were recommended to be redesigned. The purpose of machinery monitoring is to manage those components that are deemed critical with regard to mission, and consequences such as loss of life, performance, and/or cost. Based on the preliminary findings, installing health monitoring systems is feasible and beneficial for complex equipment such as generators, turbines and gearboxes. A critical need for complete validation of this technology is the acquisition of more data from multiple machines. Future monitoring systems should be "built-in" from initial design to minimize the installation difficulties. Another future application would be to combine the health monitoring data with the control system data. This data would not only improve the accuracy of algorithms but also lay the foundations to transition from diagnostics and prognostics to intelligent control.

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Feature Extraction Technique Definitions:

RMS – Root Mean Square is a time analysis feature that measures the power content in the vibration signal.

Skew – characterizes the degree of asymmetry of a distribution around it means.

Crest – a simple approach to measure defects in the time domain using the RMS approach.

Kurt – kurtosis is the fourth moment of the distribution and measures the relative flatness of a distribution as compared to a normal distribution.

Enveloping – used to monitor the high-frequency response of the mechanical system to a periodic impact such as gear or bearing faults.

EnvKurt - performs enveloping then kurtosis techniques.

EnvFrq – performs enveloping technique then looks for the frequency at the highest peak.

DemPk – demodulation identifies periodicity in modulation of the carrier.

FMO – is a method used to detect major changes in the meshing pattern.

SLF – is the sideband level factor and is used to detect a bent or damaged shaft.

S01 & S02 – are the first and second shaft order vibration amplitude levels (respectively) and is used to detect shaft imbalance or damage.

M6A & M8A –detect surface damage on machinery components.

FM4 –detect changes in vibration pattern resulting from damage on a limited number of gear teeth.

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Accelerated Capabilities Initiative
Condition-Based Maintenance: Machinery Diagnostics and Prognostics

Program Review
July 20, 2000

Presented to:

Dr. Thomas McKenna
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PENNSTATE ARL

NAVSEA

This report summarizes the technical progress of the Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics under ONR Grant N00014-96-1-1147 for the period of 1 October 1999 to September 30, 2000.

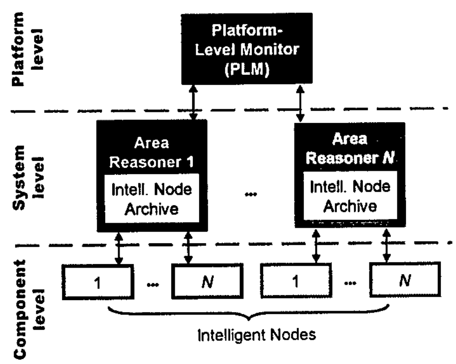
Outline

- ACI Objectives
- Team
- Approach
- ACI I Outcomes
- ACI II Activities
- FY01 Plans

This presentation will cover the following topics: ACI objectives, the research team formed to achieve the objectives, the selected approach for the program, the outcomes of the first phase of the research (ACI I), and activities for the second phase of the program (ACI II). A discussion for fiscal year 2001 plans is also included, detailing topics such as commercialization of hardware, transition of the technology to Navy applications and a shipboard demonstration of hardware. A summary of the work is also provided.

ONR ACI Goal and Objectives

- Goal
  - Extend the science and technology emerging from the MURI research to further enable prognostics and health management (PHM)
- Objectives
  - Develop a multi-layer hierarchical architecture and implement machinery health monitoring at component, machine, and system levels
  - Demonstrate the hierarchical system on a Navy application (501-K34 Ships Service Gas Turbine Generator Set)
  - Develop prototype hardware to accomplish PHM



PENNSTATE ARL

NAVSEA

The ACI program evolved from a previous program called the Multidisciplinary University Research Initiative in Integrated Predictive Diagnostics (MURI). The MURI developed several concepts critical to the ACI, including but not limited to 1) a conceptual hierarchical process to perform diagnostics and prognostics and 2) approaches to implement predictive diagnostics via sensing, modeling and reasoning.

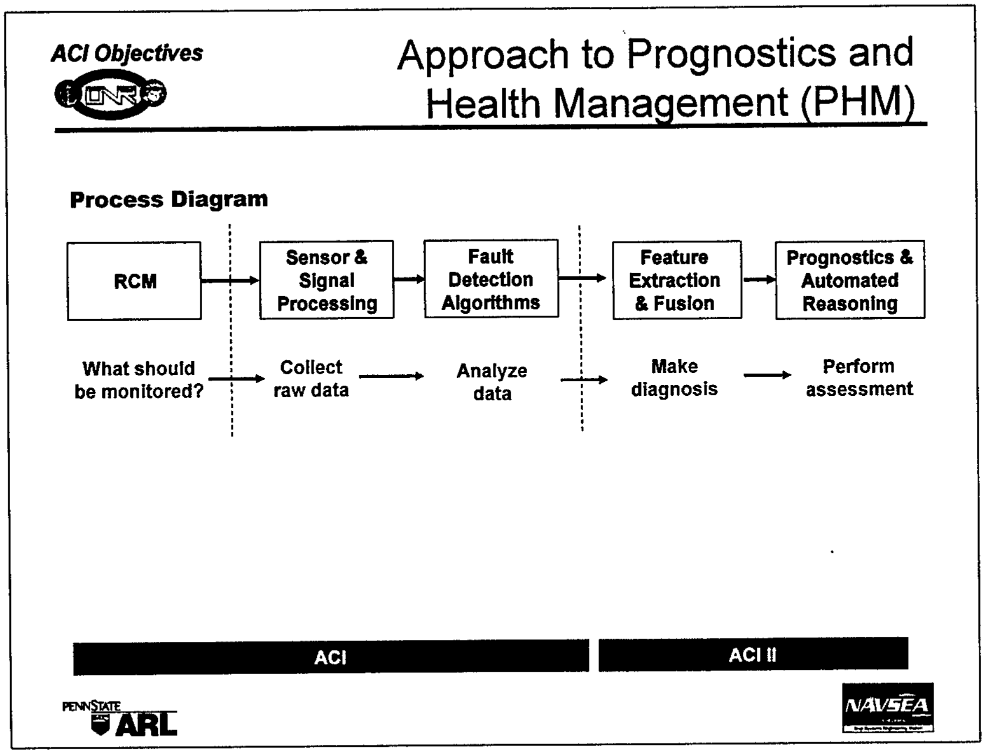
The ACI program was established to demonstrate these concepts on a selected Navy application. The 501-K34 Ships Service Gas Turbine Generator Set (SSGTG) was identified as a target platform. A three-layer hierarchical architecture was proposed, realizing the technology in hardware and software.

At the lowest level in the architecture, there are intelligent nodes (units comprised of sensors and processing and communications capability) that extract sensor data and convert that data to information. The information is reported to the next higher level where area reasoning can be performed, resulting in knowledge of a wider scope of the system. Finally, the knowledge of multiple systems can be combined at the highest level of the architecture, the platform level, where the interface with the human operator occurs. At this level decisions can be made to change the operation of the systems within operational context.

ACI Team: Government/Industry/Academia

- Allison Engine Company
- Barron Associates
- BBN GTE
- Invocon
- Logicon RDA
- Oceana Sensor Technologies
- The Pennsylvania State University
- Rensselaer Polytechnic Institute
- Tennessee State University
- University of Kentucky

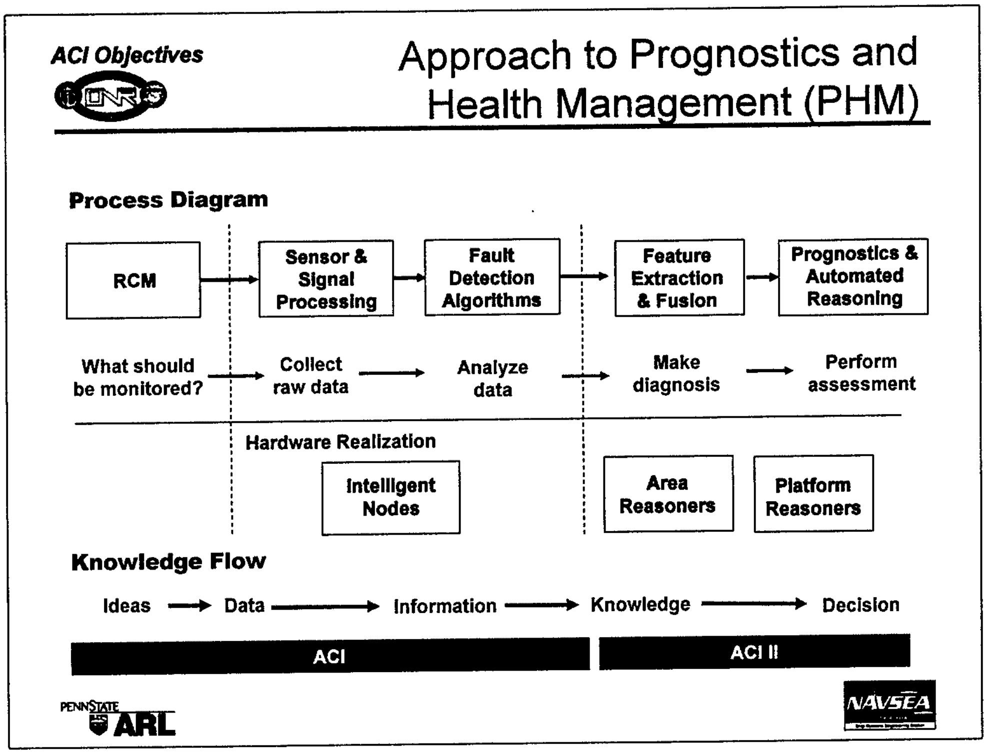
The team assembled to address implementation of the ACI objectives span industry, government and academia. Allison Engine Company is the original equipment manufacturer of the 501-K series engines. Barron Associates was an algorithm developer in machinery diagnostics. BBN GTE contributed in systems integration of the hardware and software. Invocon provided hardware development in the area of data acquisition, processing and communications. Oceana Sensor Technologies (OST) provided expertise in the area of sensor (i.e. piezoelectric) development. Rensselaer Polytechnic Institute developed algorithms for gears and bearings. Tennessee State University investigated measures of effectiveness and performance for machinery diagnostic systems. The University of Kentucky conducted research in electrical generator diagnostics.



The ACI project was also a demonstration of Prognostics and Health Management (PHM) in action. One of the most important parts of the process was a procedure called reliability-centered maintenance (RCM). RCM is a method to determine failure modes, effects and criticality analysis (FMECA). That is to say, the FMECA identifies failures requiring attention, the severity of those failures and the consequences of those failures, resulting in a prioritized list of failure modes to address. The ACI used RCM in a novel way, to not only identify maintenance opportunities, but also health monitoring opportunities.

The RCM results in a list of components to monitor, the particular failure mode of the component, the sensing technology to monitor, and the location of the sensors and potential features to track. In addition, the measures of effectiveness and performance of the monitoring system can be identified as to how well the monitoring system performs to this list.

The process continues from sensor selection, signal conditioning and processing, feature extraction and fusion leading to prognostics and automated reasoning. The process begins with a determination of what to monitor, collecting and analyzing data, making diagnosis and prognosis and performing an assessment of the health of the defined system.



This PHM process is realized in hardware and software by intelligent nodes, area reasoners and finally platform reasoners. Under the ACI, hardware was developed, along with the architecture and software to accomplish PHM. Because hardware is continually advancing, the key result of the ACI is the software architecture and detection algorithms developed. The software is portable to multiple platforms, since it was developed in standard software language C.

The hardware and software developed enables ideas to be realized in data. That data is converted to information, knowledge, and finally, decisions via the 3-layer architecture developed.

Much activity in the first phase of the ACI was related to the development of the intelligent nodes. ACI II tasks are addressing implementation of the architecture, validation of the algorithms on realistic test rigs, and preparations for shipboard demonstrations.

ACI Objectives

Critical Component Failure Mode Selection

- Shipboard Electrical Generator was picked as a critical component
- Held a workshop to involve generator experts in establishing key problem areas
  - 28 individuals attended from 15 organizations
- Of the 13 areas considered for monitoring, two were selected as key areas:

Areas Selected to Monitor	Failure Modes	Metrics to Monitor
Accessory Gearbox (6784737, 6784727)	• Bearings	• Vibration • Temperature
Electrical generator	• Rotating diodes • Winding faults • Mechanical bearings • Mechanical brushes	• Power factor • Power level • Excitation current • Output current & voltage

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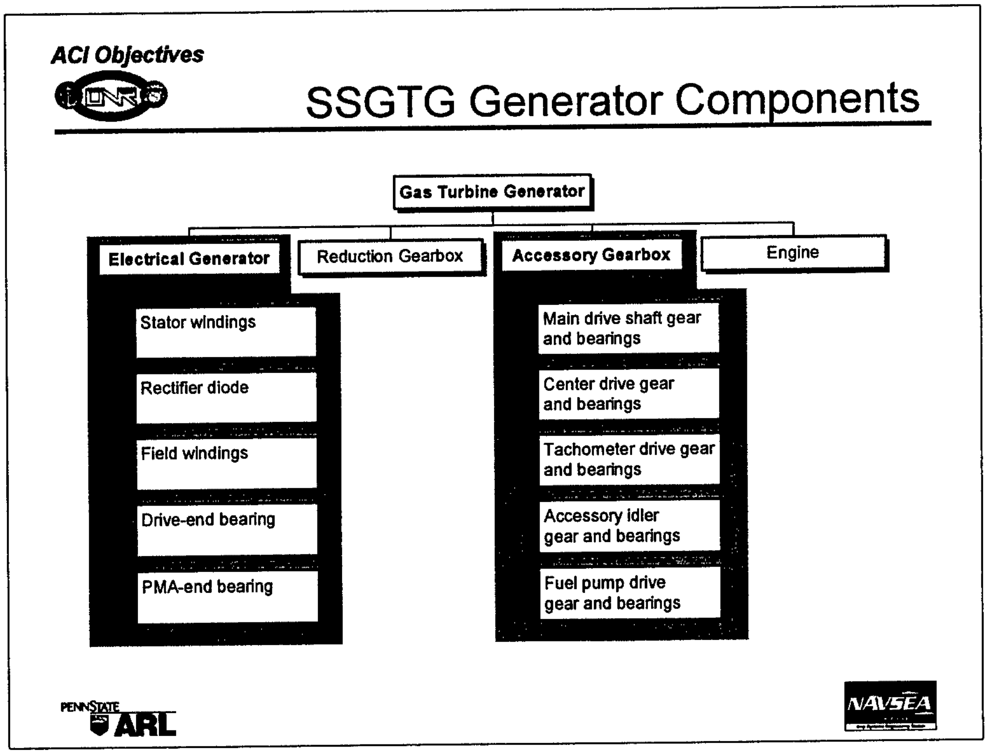
As part of the RCM process, many areas of the engine/generator set were identified at a workshop. Many sensors identified for monitoring were already on the engine, dedicated to other applications, such as control. Additional sensors were identified for the accessory gearbox and generator. Vibration, temperature, power factor, power level, excitation current and output currents and voltages were selected as parameters that could potentially be monitored using intelligent nodes.



For the generator and accessory gearbox, specific components were as follows: Stator windings, rectifier diode, field windings, drive-end bearings, PMA-end bearing; accessory main drive shaft gear and bearings, center drive gear and bearings, tachometer drive gear and bearings, accessory idler gear and bearings; and fuel pump drive gear and bearings.

ACI Objectives

Metrics Selected for Monitoring

	type	measurand	Sensor	M	PHS of Impl	SRFS Temp. F)	Output	Output	Output	Dynamic Output	Max/Min Freq.	Excitation
			EXISTING:									SIGNAL CONDITIC
1	Temp	CIT	CIT	A	2							N/A
2	Press	CDP	CDP	A	3							N/A
3	Temp	RGB	RGB - RTDs (4)	D	2							N/A
4			F. MAN. TRNSD.	A	3							N/A
			ADDITIONAL:									
5	Temp	TIT	Type K THERMOCOUPLE (6)	D	2	720		mV/deg F		1-5V *	0-1kHz	? V, A
6	Tach	PTO-rpm	PTO TAC SIGNAL	B	1	150		Hz	pulse/re	0-10V*		N/A
7	Vibe	MAS	MAIN ACCY.SHAFT GEAR VIB.	B	1	150	<100Ω	mV/G	100	0-24V	0-20kHz	ICP-CC
8	Vibe	CRB	COMP. REAR BEARING VIB.	B	1	700	<100Ω	mV/G	100	0-24V	0-20kHz	ICP-CC
9	Vibe	RGB	RGB VIB. (4)	B	1	150	<100Ω	mV/G	100	0-24V	0-20kHz	ICP-CC
10	Tach	AGB-rpm	AGB TAC SIGNAL	B	1	150						
11	Vibe	AGB	ACCY. GB. VIB. (5)	B	1	150	<100Ω	mV				
12	Temp	AGB	co-located ACCY. GB. TEMP.	C	2	150		mV/d				
13	Temp	CDT	Type K CDT TEMP.	C	3	700		mV/d				
14	Press	CIP	CIP TRANSDUCER	C	3	150		mV				
15	IRSpec	ENG oil cd	ENG/RGB LUBO Contam Det.	C	3	150		mV/IRband			0-1kHz	? V, A
16	IRSpec	GEN oil cd	GEN LUBO C.D.	A	[illegible]	150		mV/IRband			0-1kHz	? V, A
17	Load	GEN	GEN. LOAD/VIB SENSORS (2)	A	3	150		pC/lbf	18	0-24V	0-1kHz	ICP-CC
18	Load	RGB	ENG/RGB LOAD/VIB SENSORS (4)	C	3	150/700		pC/lbf	18	0-24V	0-1kHz	ICP-CC
			GENERATOR MEASUREMENTS:									
19			LOAD VOLTAGE (3)	A	2			VOLT				
20			LOAD CURRENT (3)	A	2			CUR				
21			EXCITER CURRENT (2)	A	2			CUR				

5 vibration signals

3 voltages
5 currents

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Although many signals were identified in the original sensor list shown here, the actual components and signals selected for intelligent nodes were two components with a few signal channels. After a review of this proposed sensor list, many items were not considered based on a planned redesign of the component (e.g. lube oil cooler), potential interference with the control system (e.g. thermocouples in the turbine section), physical inability and/or excessive cost to insert a sensor (e.g., main shaft bearings).

ACI I Outcomes

- Major milestones
- Accomplishments
- Algorithm summary
- Hardware options
- Instrumentation options
- Testing experience

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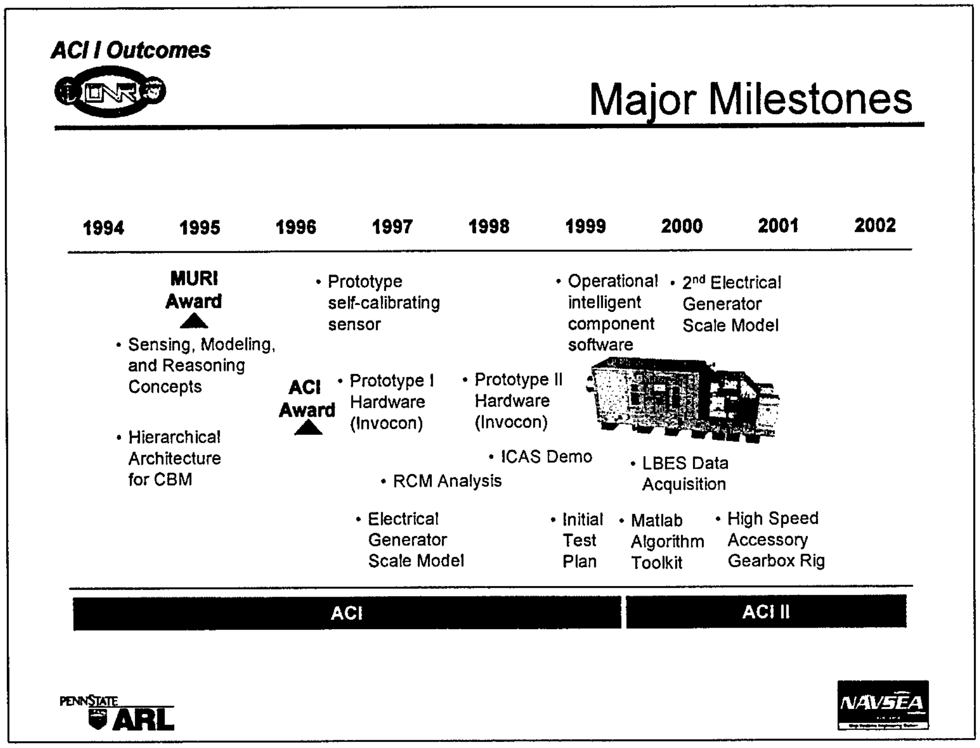
NAVSEA

Now that our overall approach of a 3-layer architecture and a process to implement PHM has been described, a review of the first phase major outcomes is described. The major milestones, accomplishments, summary of algorithm work, hardware and instrumentation options and test experience are described.



As mentioned earlier, the ACI Program had its beginnings in the MURI program. The MURI concepts of sensing, modeling and reasoning and the hierarchical architecture for CBM was developed. With the award of the ACI in mid-1996, starting from only concepts and ideas, the team developed prototype hardware and software to implement the 3-layer architecture for application to the 501-K34 SSGTG. Prototype hardware was produced by OST (self-cal sensor) and Invocon (breadboard and brassboard hardware). In parallel with the hardware development, algorithms and software were developed, resulting in an operational intelligent node with running software in late 1999. The results of the RCM analysis have not only defined the current instrumentation plan; this information is also being implemented (in a separate project) to automate water washing based on compressor performance (identified at the 1997 workshop). Also, the ability to send information from the ACI architecture into the Navy integrated and Condition Assessment System (ICAS) was demonstrated in early 1999. Preliminary tests with the wireless hardware were conducted in field tests and at the land-based engineering site (LBES) in Philadelphia to verify equipment operation. A unique scale model of the generator was constructed to investigate generator diagnostics.

The ACI also supported a number of software toolkits, potentially leading to commercial software products. The results of ACI I are now being continued with the development of additional test rigs and actual data acquisition at LBES.

ACI I Outcomes

Key Accomplishments

- **Prototype hardware** – to support three-layer hierarchical architecture
- **Open systems software** – algorithms that are portable to multiple hardware platforms
- **Test facilities unique to machinery diagnostics and prognostics** – enable ACI team to act as "trusted agents" and provide transitional data to other organizations
- **Valuable test experience and lessons learned**
- **Technology transfer**
  - Spin-off test experience and diagnostic algorithms
  - Development of intelligent node requirements
  - NSWCCD Philadelphia partnership for CBM implementation and training

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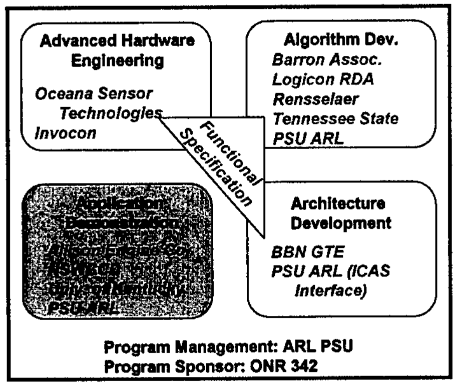
Key accomplishments of the ACI I included prototype hardware to support the 3-layer architecture and, even more importantly, the open systems software that allows the software to be ported to multiple hardware platforms. Since the prototype hardware consisted of a proprietary radio network, the value of the flexibility of the software is being realized, as the software can run on many hardware devices. Also critical is the establishment of test facilities unique to machinery diagnostics and prognostics. There are only two 501-K electrical generator models in existence (Univ of Kentucky and PSU). These facilities enable the ACI team to act as "trusted agents" and provide transitional data to other organizations. The test experience and lessons learned are of great value since they contribute to hardware and software that perform well in realistic environments. Major accomplishments in the area of technology are cited, including team members becoming active in other research projects involving machinery diagnostics, the development of intelligent node requirements and a partnership with NSWCCD Philadelphia for implementing the ACI technology in CBM and training.

ACI I Outcomes

Algorithm Summary

Techniques Investigated	Performer	Relevance
Bispectral TLO Statistical Change Detection	Barron	Bearings, gears, others
Hidden Markov Models	BBN	Bearings, gears
Phase Correlation	Logicon	Data reliability, multiple sensors
Frequency Demodulation	RPI	Bearings, gears
Measures of Performance	TSU	Overall system
Kalman Filter Feature Tracking, Comblet	PSU	Prognostics, gears
Field Voltages and Currents	Univ. of Kentucky	Windings, diodes, motors and generators



The architecture defined by the ACI must accommodate the emerging variety of algorithms shown by the team members.

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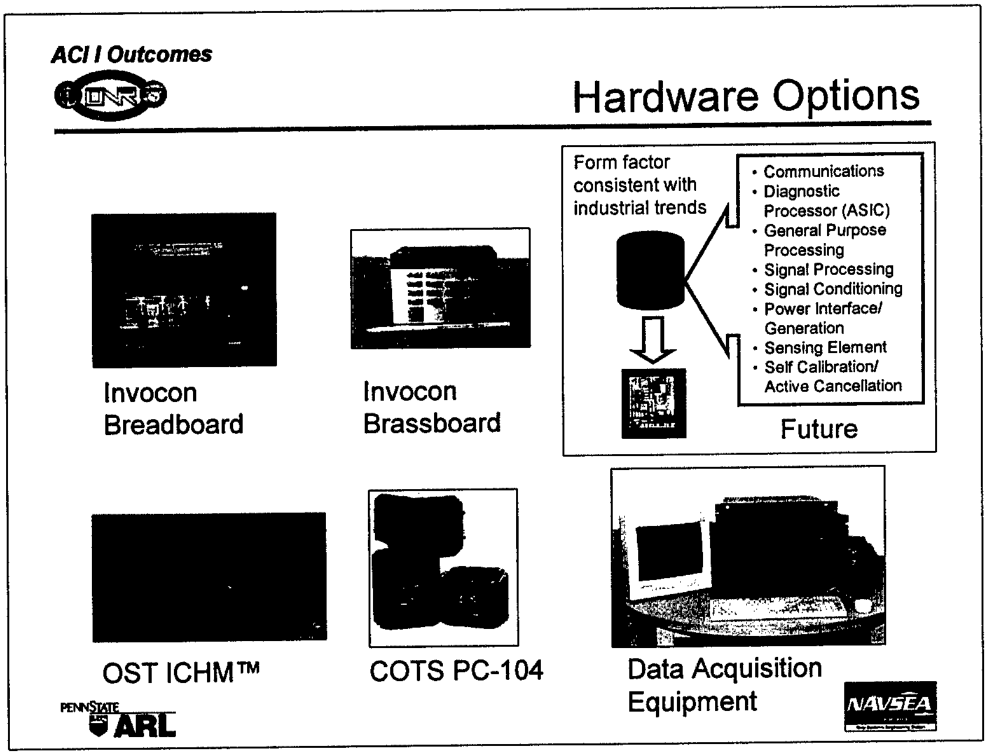
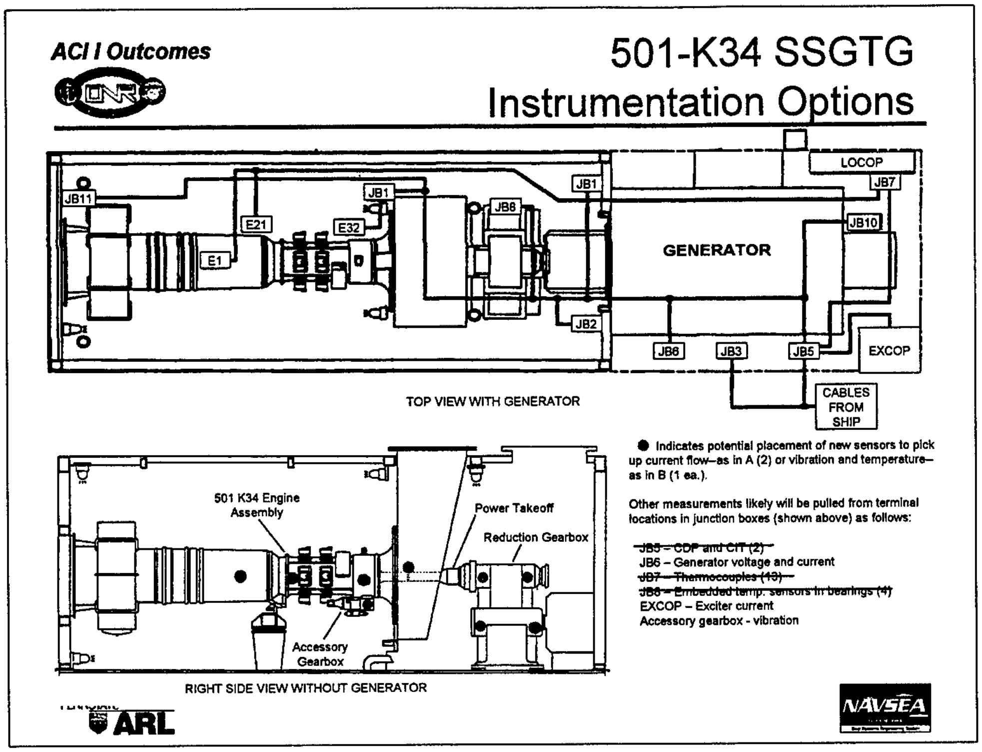
The architecture defined by the ACI must accommodate the emerging variety of algorithms shown by the team members. A list of the algorithms developed include the above techniques. These techniques have relevance to bearings, gears, motor/generator windings and diodes, data reliability, multiple sensors, system performance, and prognostics.

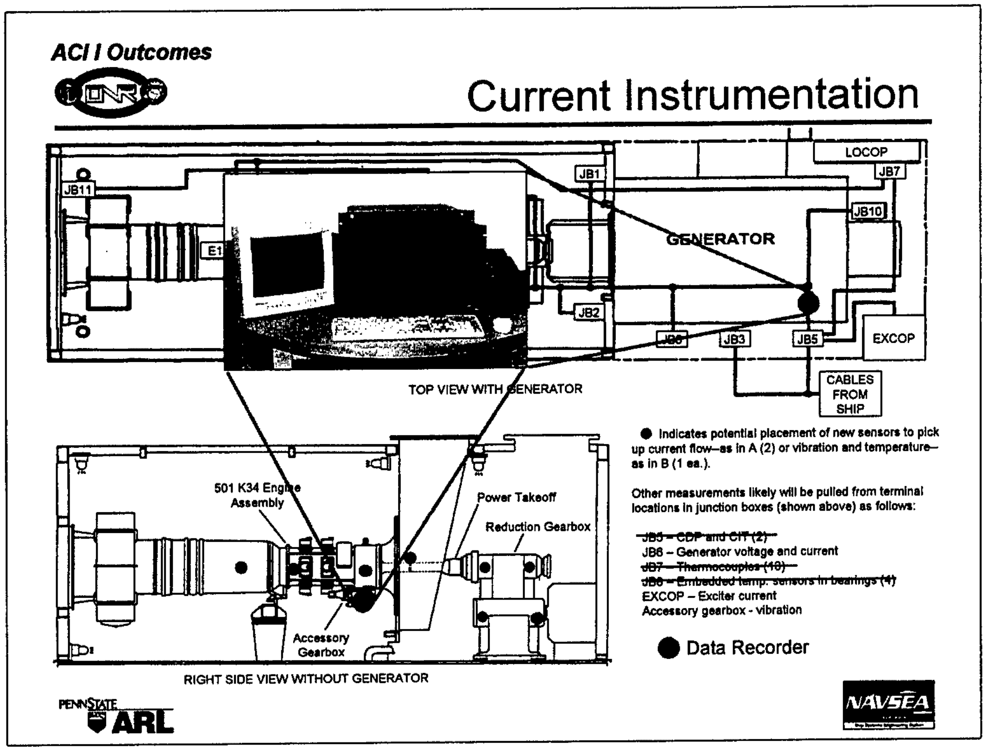
What is required now is to validate these algorithms, both in the lab test facilities and on the actual 501-K34.



Ultimately, there are many options in selecting hardware for a shipboard demonstration. Although the Invocon hardware has a proprietary radio network and will not be selected for shipboard demonstration, the nodes developed will support testing and development of specifications for alternative hardware. The hardware selected will be consistent with industrial trends. Currently, a data acquisition package is being used to gather data. Once that data has been analyzed, specifications will be generated for the intelligent node hardware. The ACI program would like to consider the best technologies within schedule and budget to accommodate a shipboard demonstration. Other intelligent nodes such as OST's ICHM™ and COTS hardware will also be reviewed for application to the shipboard demonstration.



A good understanding of applying PHM and RCM to a fielded machine has produced a number of options for acquiring data. In particular, many of the signals that were originally identified as monitoring applications are actually included in the control system. Of the original areas selected, only the generator and accessory gearbox remain as candidates for using intelligent nodes. Many of the remaining areas can be addressed by the Full Authority Digital Electronic Engine Control (FADEC). For LBES applications, the instrumentation can include the data acquisition package, intelligent nodes and FADEC processing of sensor data. For shipboard and future applications, the instrumentation can include intelligent nodes and FADEC processing. Currently at LBES, a data acquisition package consisting of a rack mounted computer and data acquisition card is being used to gather high-fidelity data.


ACI I Outcomes
Current Instrumentation
LOCOP
JB7
JB1
JB11
JB10
E1
GENERATOR
JB2
JB3
JB5
EXCOP
CABLES FROM SHIP
TOP VIEW WITH GENERATOR
501 K34 Engine Assembly
Power Takeoff
Reduction Gearbox
Accessory Gearbox
RIGHT SIDE VIEW WITHOUT GENERATOR
● Indicates potential placement of new sensors to pick up current flow—as in A (2) or vibration and temperature—as in B (1 ea.).
Other measurements likely will be pulled from terminal locations in junction boxes (shown above) as follows:
~~JB5 – CDP and CIT (2)~~
JB6 – Generator voltage and current
~~JB7 – Thermocouples (16)~~
~~JB8 – Embedded temp. sensors in bearings (4)~~
EXCOP – Exciter current
Accessory gearbox - vibration
● Data Recorder
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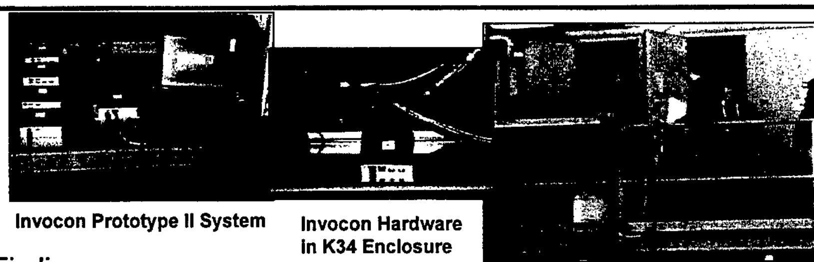
ACI I Outcomes

Testing Experience



Invocon Prototype II System

Invocon Hardware in K34 Enclosure

Radio Signal Strength Tests (LBES Feb '99)

Findings:

- Wireless communications will work in shipboard environments
- Nodes can communicate from within enclosures
- Sensor access to components is limited (e.g., thermocouples in turbine)
- Vibration intelligent nodes are high value added
- Tapping existing sensors on legacy equipment is non-trivial

Related field tests:
- Sundstrand
- GE IMATE
- ICHM DUAP
- Pratt & Whitney
- Ex-USS Shadwell
- AAAV

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Important test experience was accomplished resulting in several findings. For example, we determined that wireless communications will work in shipboard environment, intelligent nodes can communicate from within enclosure, sensor access to components is limited, vibration nodes are high value added, and tapping existing sensors on legacy equipment in nontrivial.

Also, test experience in the ACI is contributing to related programs, such as PSU's involvement in Hamilton Sundstrand and the GE IMATE program. Other experience is being obtained in ICHM DUAP and AAAV.

ACI II Authorized Tasks

- Validation
  - Perform data acquisition at LBES
  - Validate algorithms on test rigs and LBES
  - Perform testing on electrical generator and accessory gearbox rigs to provide fusion of vibration data with electrical subsystems
- Shipboard demonstration
  - Develop appropriate technical specifications
  - Seek approval and support from equipment owners
  - Implement technology based on ship availability

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For ACI II, emphasis is placed on validation of the ACI developed hardware and software. Since the software will be transitioned to the fleet, this phase is focusing on data acquisition at LBES, algorithm validation on test rigs and LBES, and testing on the electrical generator and accessory gearbox rigs to provide fusion of vibration data with electrical subsystems.

The ACI II will also focus on a shipboard demonstration of the developed technology. This will include developing appropriate technical specifications, obtaining approval and support from equipment owners, and implementing the technology based on ship availability.

ACI II Tasks

The Need for LBES Testing

501-K34 Ships Service Gas Turbine Generator Set

- Land-Based Engineering Site (LBES)
  - Provides configuration control for shipboard equipment
  - Allows system performance to be investigated during training and engineering tests
  - Provides the most realistic data prior to systems being released to ships
- Qualification procedures
  - Gas Turbine Bulletin #14
  - Design, Development, and Implementation Programs (DDIP)

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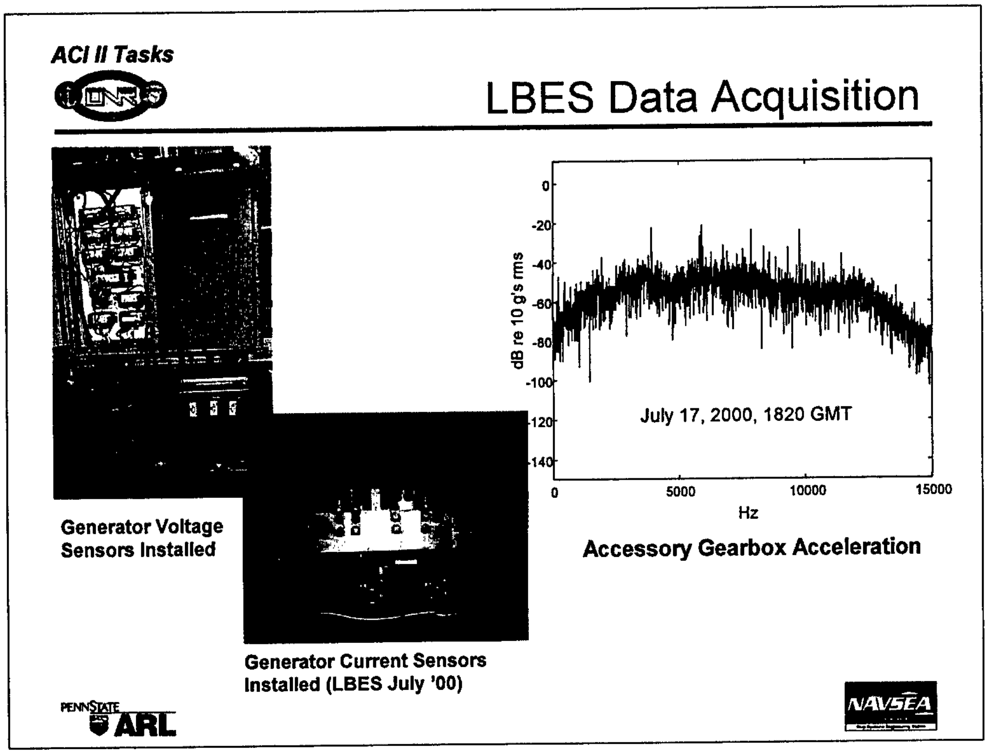
Before technology is released to the fleet, it must be approved. The LBES is managed by NSWCCD Philadelphia. NSWCCD provides configuration control for shipboard equipment. The LBES enables system performance to be investigated during training and engineering tests. The ACI will collect data while other tests are being performed to reduce testing costs. The LBES also provides the most realistic data prior to releasing systems to the fleet. Additionally, NSWCCD provides engineering support to the fleet.

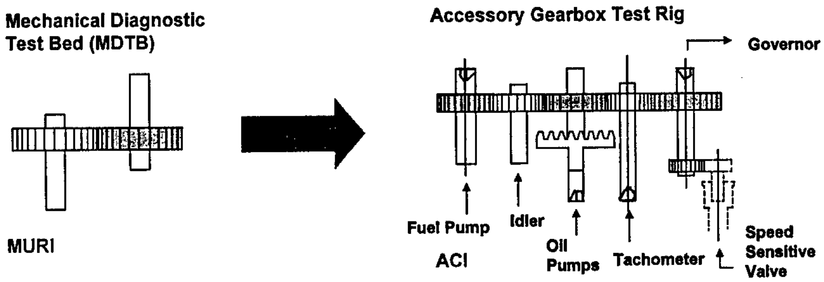
Qualification for shipboard equipment is determined by the procedures according to Gas Turbine Bulletin #14 and the Design, Development and Implementation Program (DDIP).



Currently, instrumentation and data acquisition are in process at LBES.

ACI II Tasks

Development of Complex Testing Facilities



- Fully realizing prognostic capability requires this test facility for:
  - Generating additional transitional data
  - Producing and verifying trackable features

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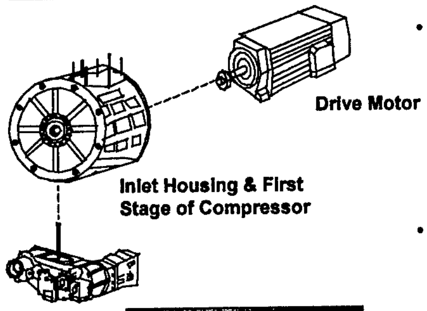
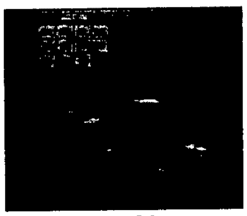
The accessory gearbox represents an increase in complexity of the analyzed component. The research and the experimentation performed on the Mechanical Diagnostics Test Bed under the MURI program validated the algorithms and underscored the importance of a complex test facility. The ACI must generate additional transitional data and trackable features on the more complex Accessory Gearbox Test Rig rig to realize true prognostics capability.

ACI II Tasks

High Speed Accessory Gearbox Test Rig





Components of Accessory Gearbox Test Rig

- Investigate behavior of accessory gearbox under laboratory conditions
  - Design test rig to simulate operating conditions
  - Instrument gearbox
  - Obtain vibration spectra
  - Compare to data obtained at LBES
- Technical Issues:
  - Alignment
  - Blade pass frequencies
  - Bearing configuration (Barden Split Cage)

	No. Teeth	Speed	Frequency (Hz)
Fuel pump	27	3487	1569
Idler	35	4520	2637
Oil pump	16	3487	930
Idler (tachometer)	35	4520	2637
Governor	27	3487	1569

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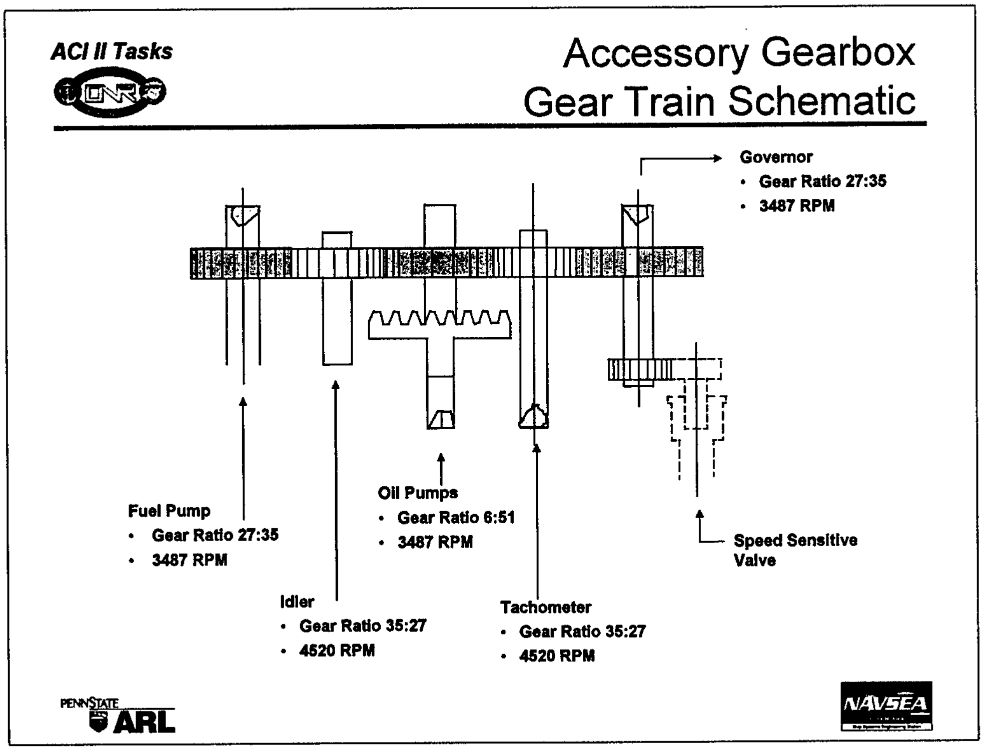
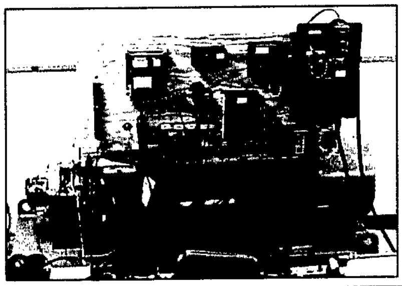
This rig is being assembled in cooperation with NSWCCD Philadelphia. Using a borrowed accessory gearbox, the ACI team is analyzing the behavior of the gearbox under laboratory conditions. Technical issues associated with alignment, bearings and blade pass frequencies will be addressed.



The accessory gearbox is connected to many component systems of the engine including the fuel, oil, and speed sensing systems. Additionally, many of the gears operate at the same speed and gear ratio, posing a challenge to identifying faults along a particular driveline.

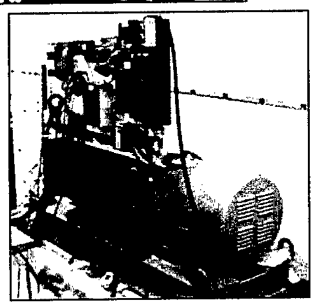
ACI II Tasks

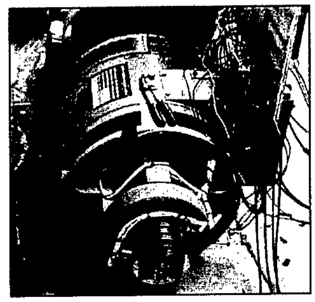
Area Reasoner-Level Data Fusion: Electrical Generator Test Rig



- Scale model for 501-K34 electrical generator
- Distinguish electrical vibration from mechanical bearing faults
- Reduce potential false alarms

Performers: Univ. of Kentucky, RPI, PSU





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One example of data fusion to be investigated involves distinguishing electrically induced vibration from mechanical bearing faults. This case also addresses false alarm reduction, since without knowledge of the electrical performance, vibrations can be misinterpreted as a bearing problem. The electrical diagnostics and preliminary test plan will be discussed by the University of Kentucky and RPI.

ACI II Tasks

Technical Observations from Experience to Date

Implementation of machinery prognostics requires:

- A library of operational data
- Algorithm validation on realistic systems
- Field-tested hardware/software
- False alarm control
- Fusion of vibration data with other mechanical and electrical subsystems
- Automated reasoning for platform and fleet monitoring
- Appropriate technical specifications
- Approval and support from equipment owners

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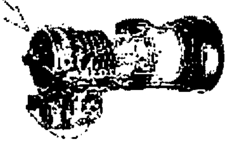
Based on experience to date, implementation of machinery prognostics requires operational data, realistic validation, field-tested hardware/software, false alarm control, fusion of vibration data with other mechanical/electrical systems, automated reasoning for platform and fleet monitoring, appropriate technical specifications, and approval and support from equipment owners.

ACI II Tasks

A Pathway for PHM Transition

- Science and technology poised for transition
- Potential application on 501K and LM2500
- Vital enabling efforts for transition realization
  - FADC integration of algorithms
  - High-level algorithms, data fusion, and reasoning
  - Support for LM2500

LM2500
- Power: 21MW
- Drives propulsion



501K
- Power: 3MW
- Provides ship's electrical power

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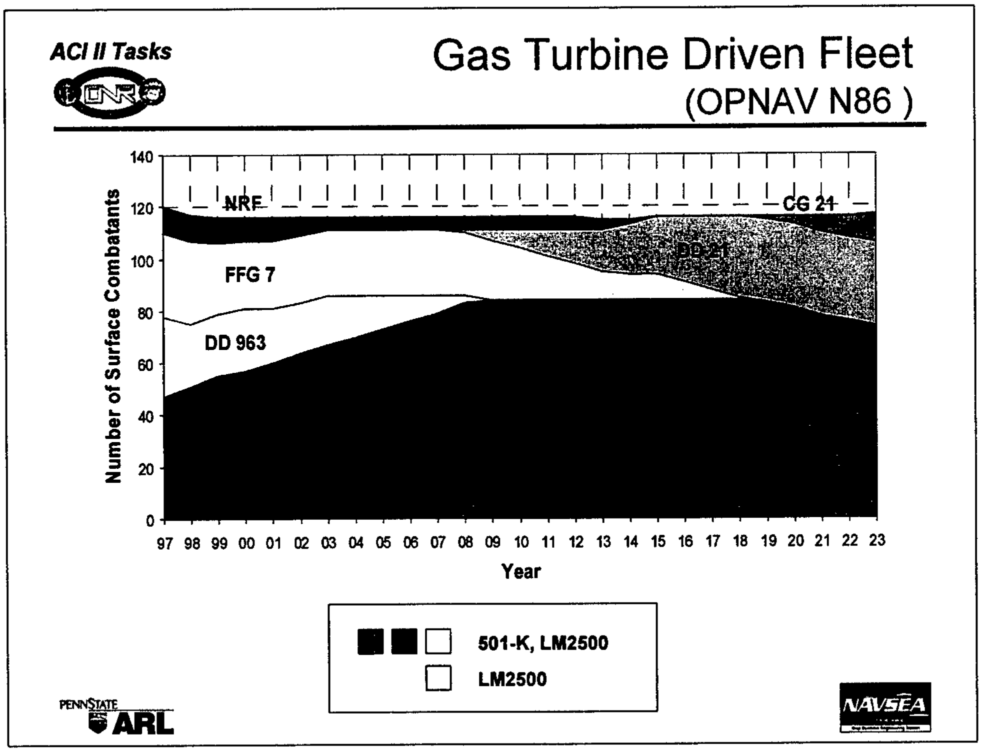
The technology developed by the ACI is at the point where insertion into the fleet is feasible and do-able. One potential pathway to realize PHM transition is via the FADEC. Upgrades to the FADECs for the 501K and the LM2500 are being planned. These two applications represent a large portion of the fleet and represent real opportunities for implementation of PHM technology. The ACI has focused on the 501K series; therefore, additional support for the LM2500 must be addressed.



As indicated by this chart, the 501-K and the LM2500 are used in most Navy ship applications.

FY01 Plans

- Data acquisition and testing
  - Test rigs/LBES
- Validation of algorithms
- Shipboard demonstrations
  - Hardware/software availability
  - Support for NSWCCD for shipboard installation
  - Ship schedules, approvals
- Support for LM2500
- FY02 Plans

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For the discussion section of our presentation, plans for FY 2001 are presented. The main topics will include but are not limited to data acquisition and testing, validation of algorithms, shipboard demonstrations and support for the LM2500 as part of the transition plans. The current gas turbine transition plan calls for implementation of CBM technology starting in FY03, necessitating preparatory efforts in fiscal years 01 and 02.

NAVSEA PHILADELPHIA PROPULSION & POWER SYSTEMS DEPARTMENT

Gas Turbine Condition-Based Maintenance

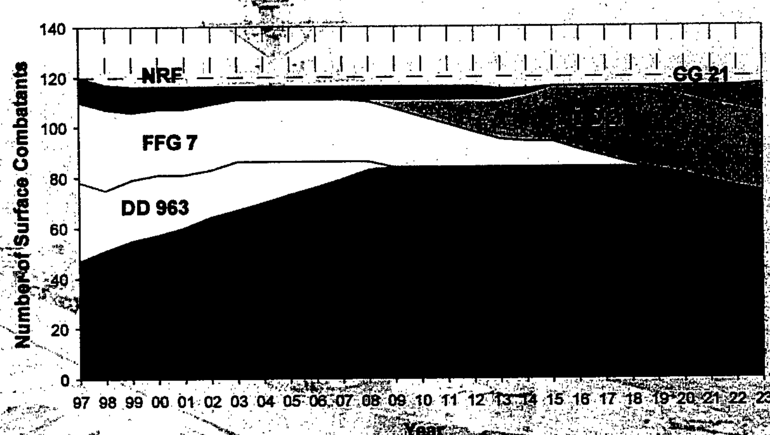
Gas Turbine CBM Transition Plan

CBM - Maintenance Based on Evidence of Need

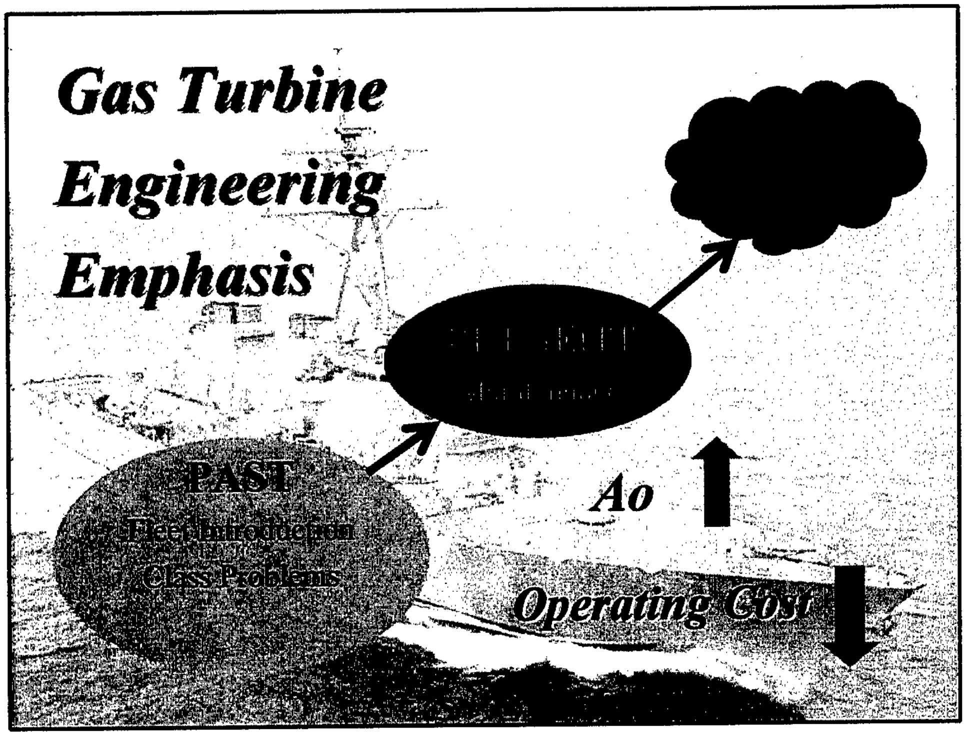
Jack McGroarty
NSWCCD 9334
(215) 897-7307

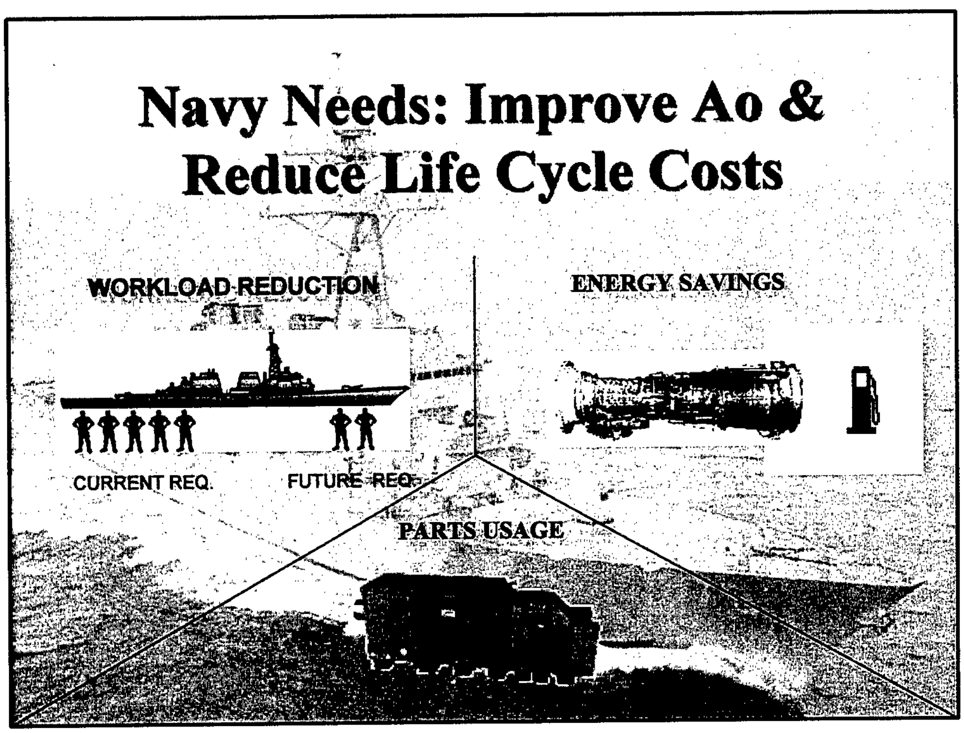
19 July 2001

Gas Turbine Driven Fleet



- New ships and legacy fleet must be totally
  - Interoperable
  - Compatible
  - Supportable
- Legacy Fleet
  - Is sizable
  - Will be with us for some time
  - ...supported


Gas Turbine
Engineering
Emphasis
PAST
Fleet Introduction
Class Problems
Ao
Operating Cost


Navy Needs: Improve Ao &
Reduce Life Cycle Costs
WORKLOAD REDUCTION
ENERGY SAVINGS
CURRENT REQ.
FUTURE REQ.
PARTS USAGE

What Is CBM

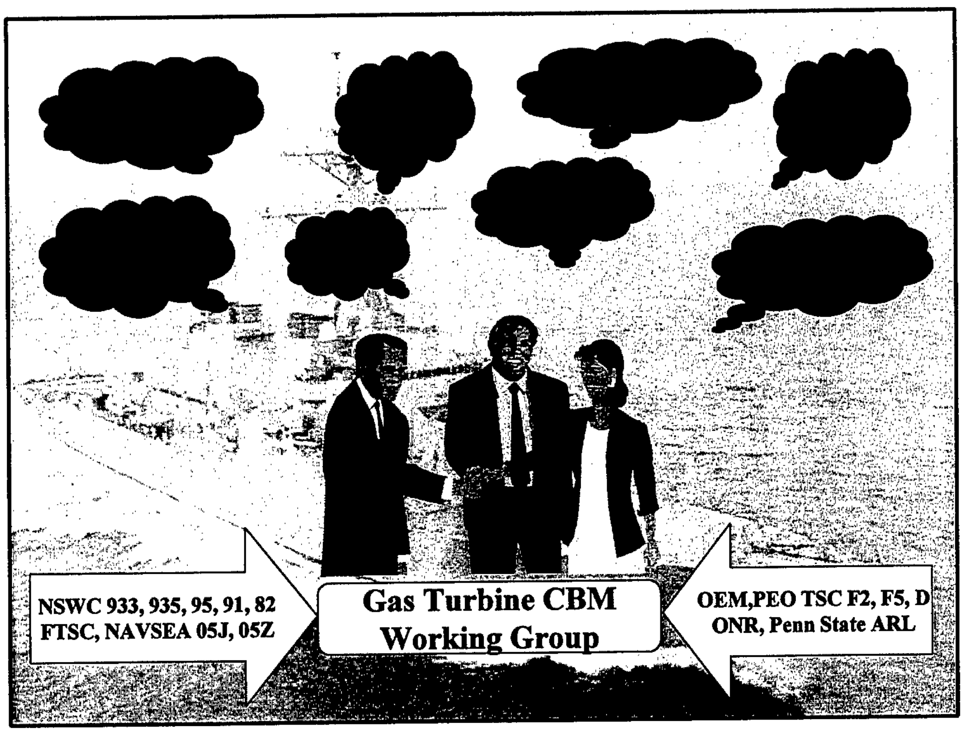
- *Condition Based Maintenance*
  - Maintenance conducted based on equipment condition
  - Become a catch all for computer stored data utilized to make recommendations/decisions on maintenance, trouble isolation, diagnostics and prognostics.

Why CBM for Gas Turbines

- Maintain or increase Ao on aging equipment through equipment health awareness and smarter operation
- Obsolete engine controls, increasing failures
- Strong Navy need to reduce operating cost
- Opportunity to unify and utilize existing technologies

CBM Objective

- The objective of CBM is to allow the Navy to meet it's primary operational objectives while increasing operation availability with reduced life cycle cost.
- In practical use, it allows the Navy to:
  - Properly manage "O" level maintenance.
  - Make best use potential equipment life.
  - Reduce troubleshooting and downtime.
  - Reduce catastrophic primary and secondary equipment [illegible]

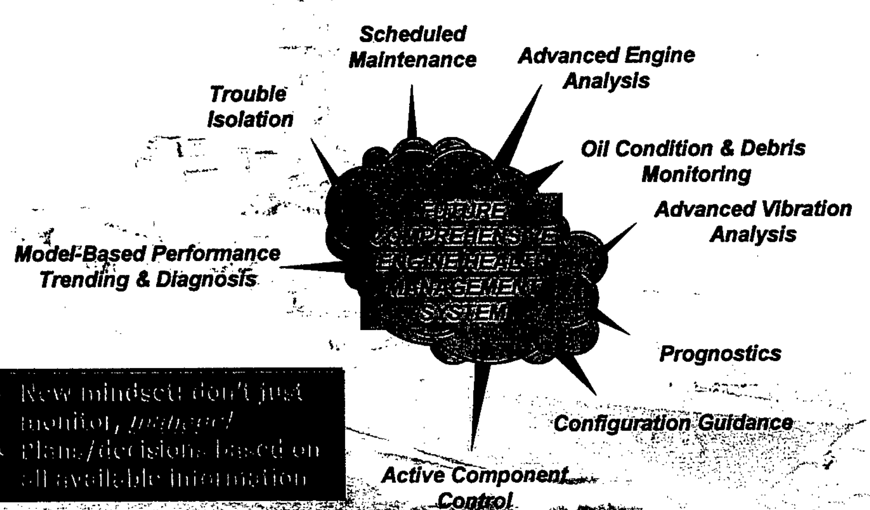


GTM/GTG Condition Processing

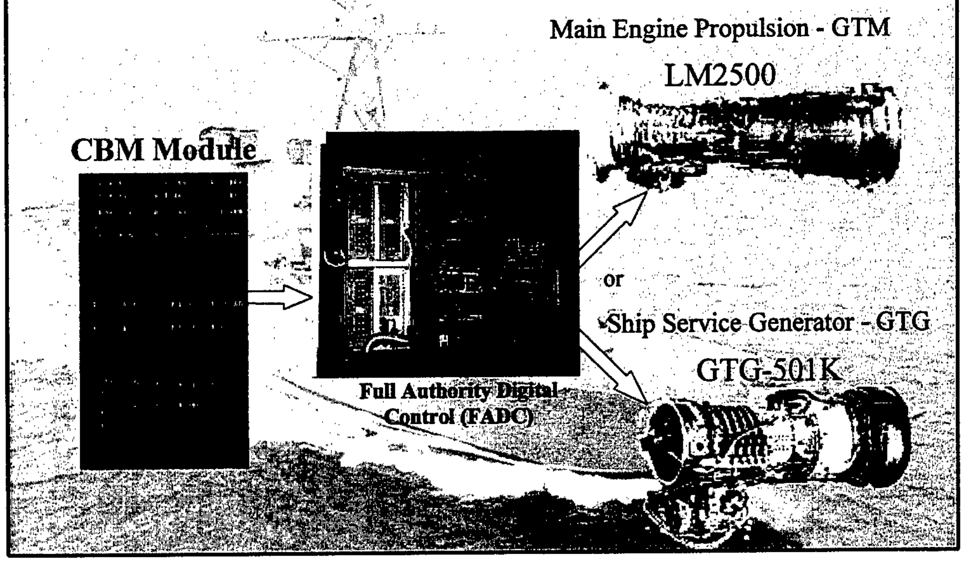
- The thrust of CBM development is to push technology and condition processing to the lowest level possible using existing technology.
- Reduces need for excessive information flow and growth of the ship's infrastructure as the CBM network is expanded to all ship systems and components.

ENGINE HEALTH

Obtaining Knowledge from Data



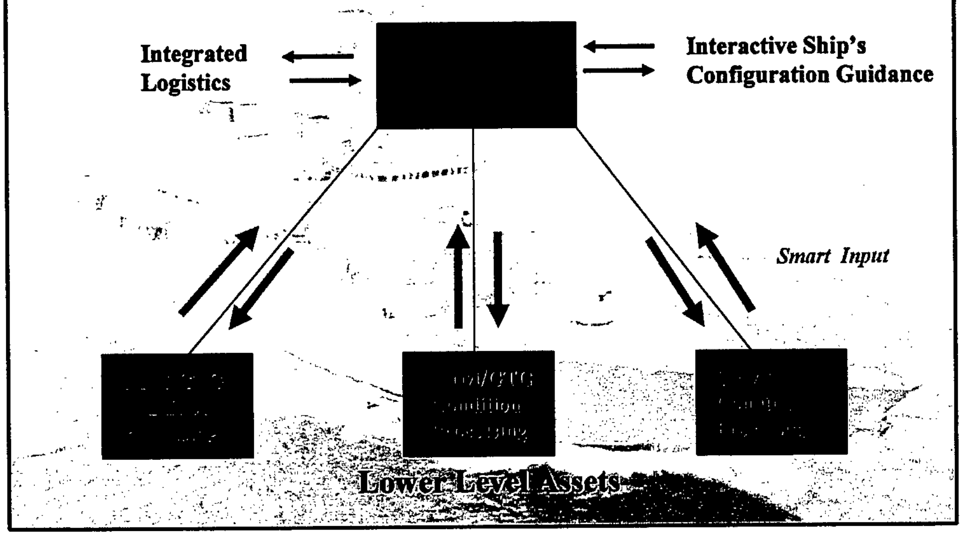
CBM Modules Enhance FADC's Capabilities



Condition Based Maintenance

- A higher level management system, provides interactive guidance, to ships crew, of proper configuration and alignment.
  - Based upon smart input from lower level assets (GTGs/GTMs).
- This configuration can be made in the most plant efficient alignment possible.
  - Further meeting the reduction of life cycle cost through energy conservation.

Future CBM Configuration



Gas Turbine Condition-Based Maintenance Transition Plan

Phase I - Planning
✓ POM-02 process
✓ Develop CBM priorities for existing PMS
✓ Develop Transition Plan

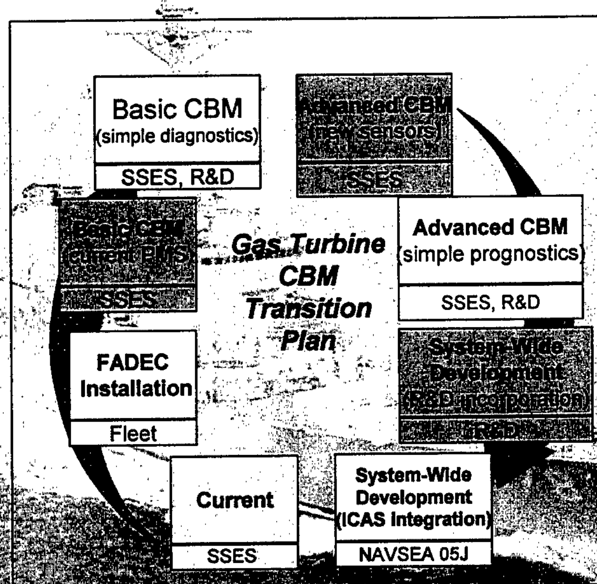
Phase II - Basic CBM
✓ FADC development and installation
➢ CBM software development for existing sensors
➢ Initial FADC-ICAS interface
- Maintenance Engineering Library (MELs) development

Phase III - Advanced CBM
➢ Limited new sensors to expand CBM
- Full integration with 3M system
- Life cycle support process

Phase IV - System-Wide Development
- Tie in R&D sensors and software
- Full ICAS tie in and support with on-shore data

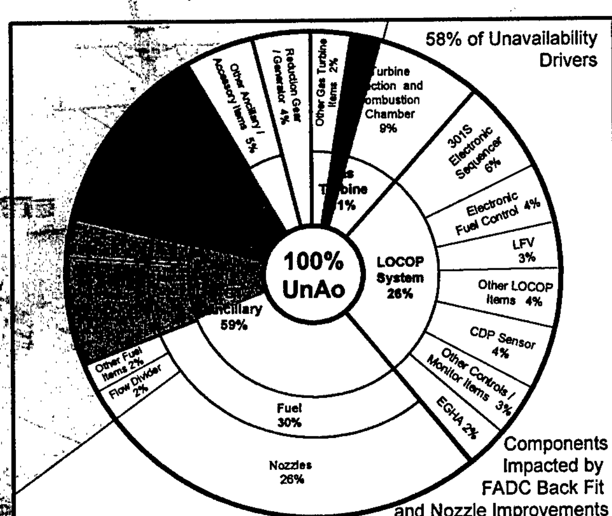
✓ Completed
➢ Working

CBM Transition Plan Overview

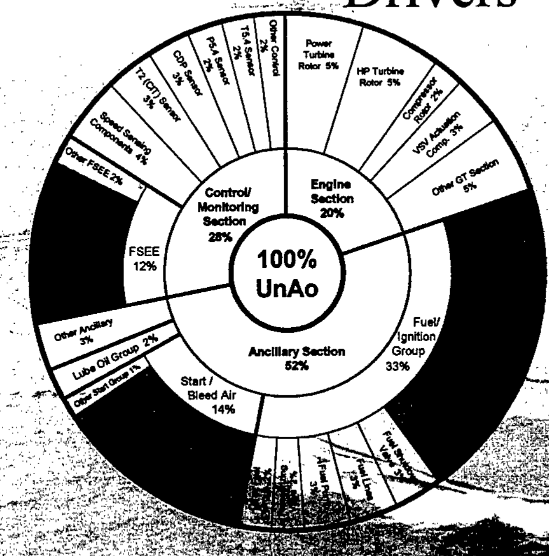


Allison 501-K34 GTG Readiness / Downtime Drivers

(01JAN99 thru 31DEC99)



LM2500 Readiness/Downtime Drivers



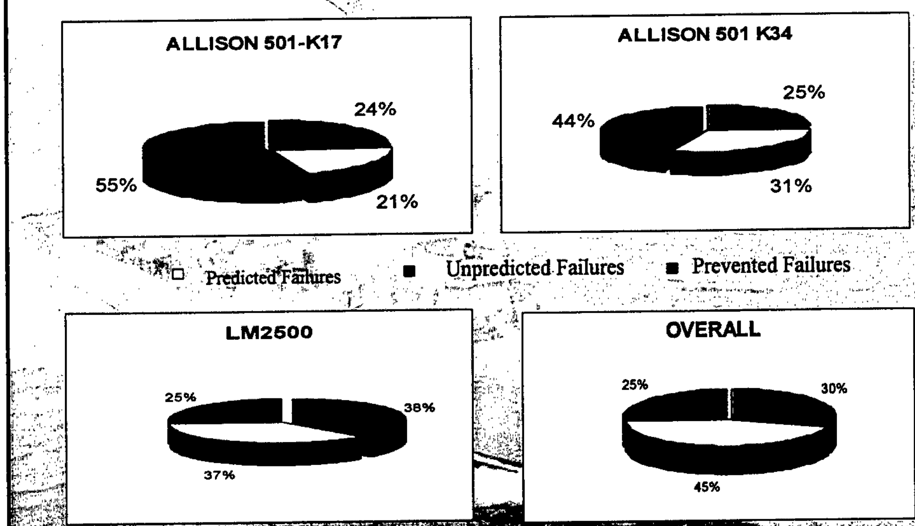
IMPROVEMENTS BEING INSTALLED	
CHANGE ID	DESCRIPTION
ACN 1A	Starter Improved T/S Guidance
ACN 1A	Main Fuel Control Improved T/S Procedures
ECP N282	Improved PLA
ECP 2503	FSEE Cooling Fan Modification
	Smartship ISC

PROTOTYPE/DESIGN DEVELOPMENT	
ITEM	DESCRIPTION
Start Valve	Marotta Prototype under Evaluation
Starter	System Dehydrator under Investigation
	Continuous Lube Starter Evaluation Underway at LBES

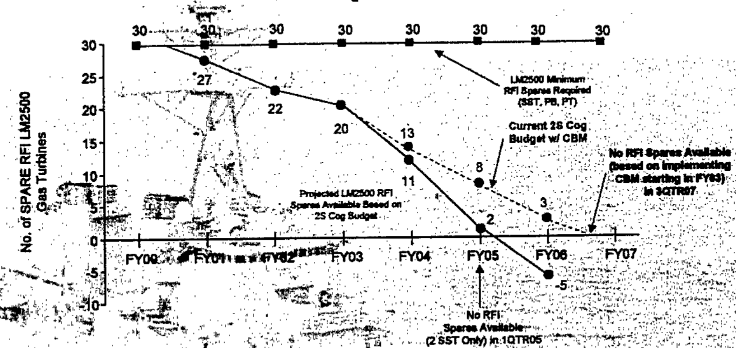
Engine Overhaul Impact

- Identify and Review 2yrs. Engine Failures for LM2500 & 501-K17/34.
- With existing Technologies, if implemented on all Gas Turbines what Impact would occur of current failures?
- Based on criteria, data was reviewed to identify Predicated and Prevented failures.

Engine Overhaul Impact

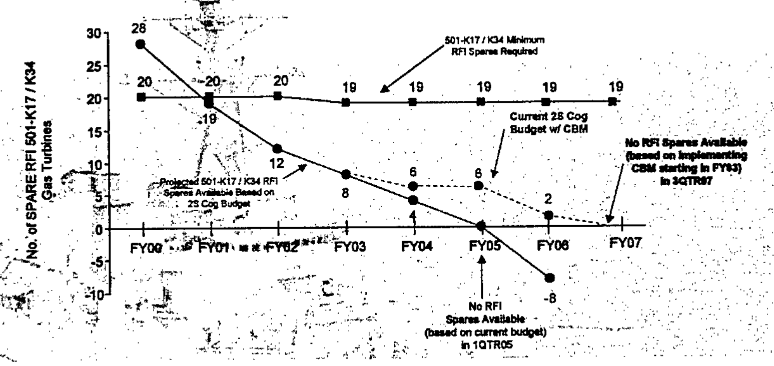


LM2500 RFI Assets and the Predicted Impact of CBM



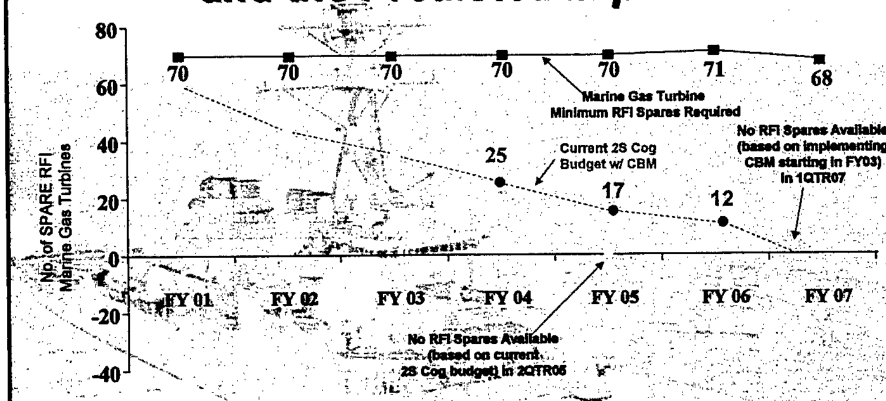
- 2S Cog Budget
  - Budget Cuts Create Program Risks
    - Spare RFI Supply is ***Depleted*** in FY 05 Timeframe under Current Budget
  - CBM Implementation would Defer Depletion of the RFI Pool by 19 Months
    - CBM Results in Increased LM2500 Readiness due to Reduced Downtime

501-K RFI Assets and the Predicted Impact of CBM

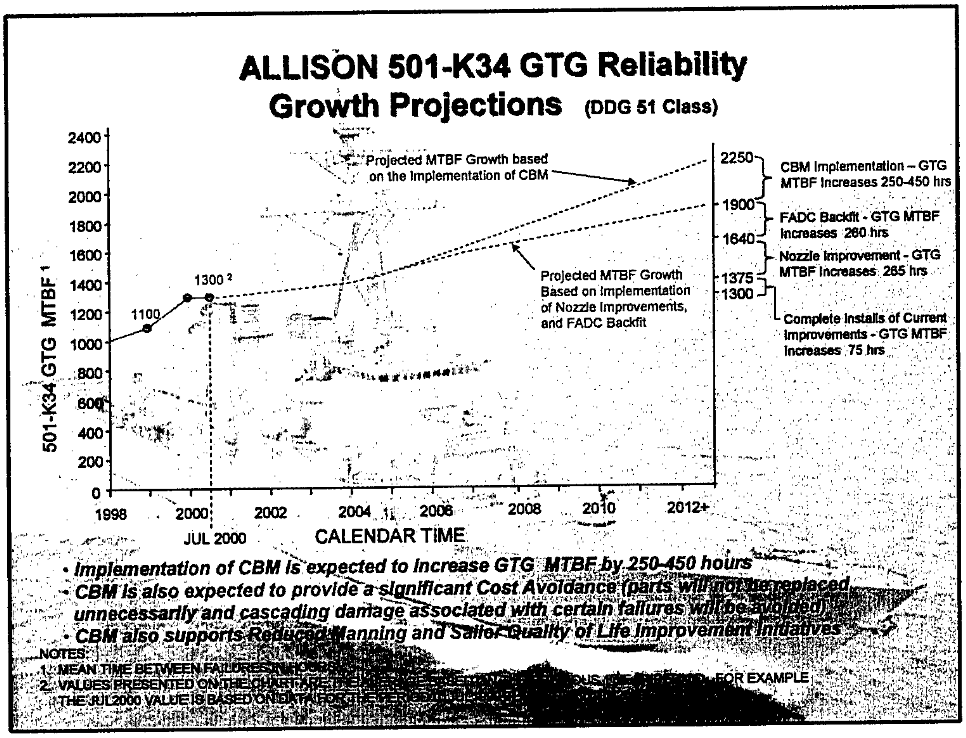


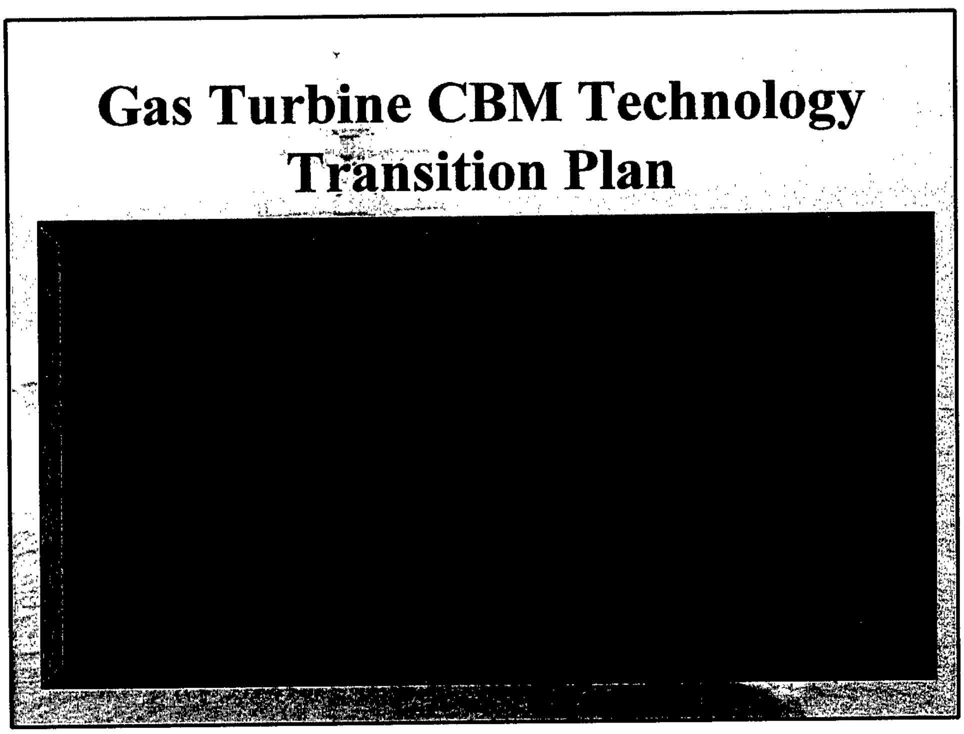
- 2S Cog Budget
  - Budget Cuts Create Program Risks
    - Spare RFI Supply is ***Depleted*** in FY 05 Timeframe under Current Budget
  - CBM Implementation would Defer Depletion of the RFI Pool by 22 Months
    - CBM Results in Increased 501-K Readiness due to Reduced Downtime

MGT RFI Asset Projection and the Predicted Impact of CBM

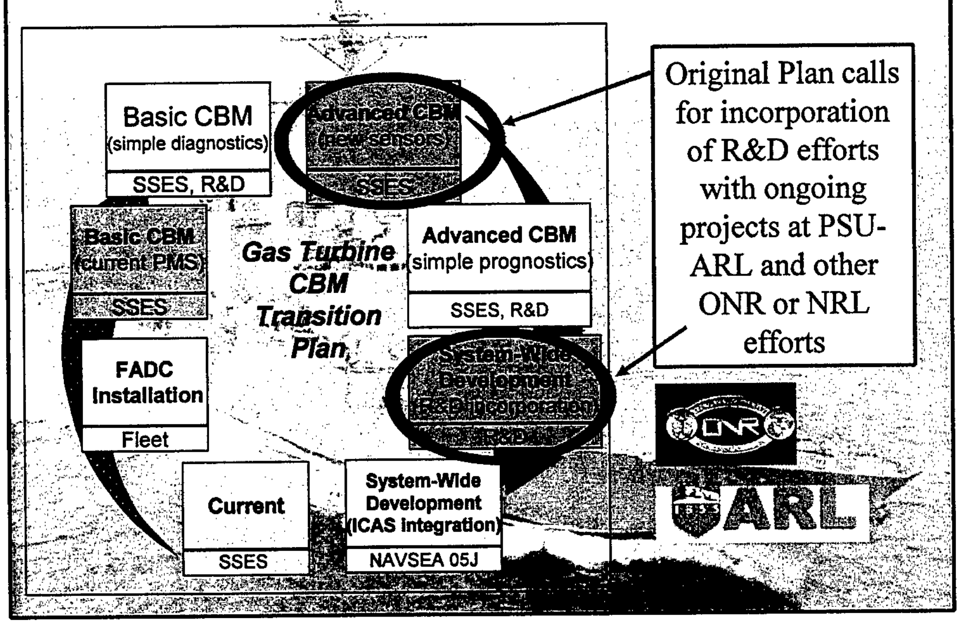


- Aggressive Implementation of CBM can Significantly Impact 2S Cog / RFI pool
  - CBM can help to Alleviate 2S Cog Budget Shortfalls
  - Increase MGT Readiness through Reduced Downtime
    - CBM is Projected to Defer Depletion of RFI Pool by 20 Months
  - RFI Pool includes All MGTs (501-K17/34, LM2500, Solar, T40B/TF62, RIMSS)


ALLISON 501-K34 GTG Reliability
Growth Projections (DDG 51 Class)
501-K34 GTG MTBF [1]
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1100
1300 [2]
Projected MTBF Growth based on the Implementation of CBM
Projected MTBF Growth Based on Implementation of Nozzle Improvements, and FADC Backfit
2250
1900
1640
1375
1300
CBM Implementation – GTG MTBF Increases 250-450 hrs
FADC Backfit - GTG MTBF Increases 260 hrs
Nozzle Improvement - GTG MTBF Increases 265 hrs
Complete Installs of Current Improvements - GTG MTBF Increases 75 hrs
1998
2000
2002
2004
2006
2008
2010
2012+
JUL 2000
CALENDAR TIME
• Implementation of CBM is expected to Increase GTG MTBF by 250-450 hours
• CBM is also expected to provide a significant Cost Avoidance (parts will not be replaced unnecessarily and cascading damage associated with certain failures will be avoided)
• CBM also supports Reduced Manning and Sailor Quality of Life Improvement Initiatives
NOTES:
1. MEAN TIME BETWEEN FAILURES
2. VALUES PRESENTED ON THE CHART ARE
FOR EXAMPLE
THE JUL2000 VALUE IS BASED ON DATA FOR THE

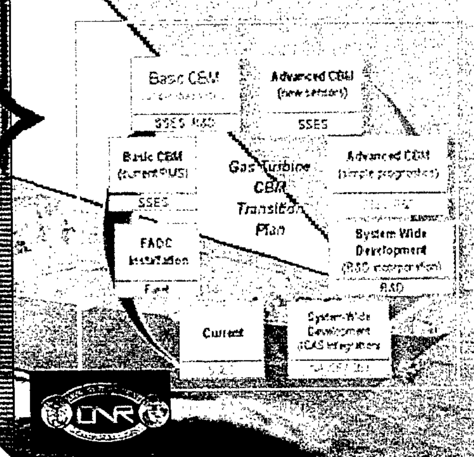

Gas Turbine CBM Technology
Transition Plan

CBM Transition Plan Overview



Plan for Technology Transition

- FY01 identify current R&D efforts directly impacting plan
- Prognostic goals developed FY02
- Sensor development through FY04
- Advanced R&D on prognostics through FY05
- Early R&D testing at LBES of algorithms and prognostics in FY03
- Full transition of sensors, algorithms and prognostics by end of FY05 (testing at LBES)
- Incorporation of sensors, algorithms and prognostics to the Fleet by FY06
- Packaged delivery to Fleet through DDIP process



Ongoing and Required R&D Efforts Impacting Gas Turbine CBM

Ongoing
- Accessory gear box testing at PSU-ARL
  - POC Les Johnson
- Automated Oil Analysis at ONR (AAAV work)
  - POC Mike Kiley
- Engine health assessment at ONR (AAAV work)
  - POC Mike Kiley

Future
- Transitioning oil parameters into meaningful CBM triggers
- Meaningful engine health assessment for gas turbines

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ARL Focus on Oil Monitoring and Analysis

May 22, 2002

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Failure Mode Assessments

Lubrications systems have many types of fault effects coupled with oil systems

⇒ Common focus is production of wear debris which occurs during initial break-in, stable wear over component life, and abnormal wear due to component damage or lubrication failure.

⇒ Common wear mechanisms include pitting fatigue of gears or bearings, abrasion, scuffing, corrosion, and "three-body abrasion wear".

Gear Faults	Bearing Faults
Plastic Deformation	Surface Wiping
Pitting	Fatigue
Heavy Scuffing	Fretting
Chipping and Tooth Crack	Foreign Debris
Tooth Breakage	Spalling
Case Cracking	Inadequate Oil Film
Surface Fatigue	Overheating
Abrasive Wear	Corrosion
Chemical Wear	Cavitation Erosion

Wetted Component Faults

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Faults Associated with Oil Quality Issues

Oil Quality Issues

[redacted]

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Faults Associated with Oil Delivery (Mechanical) Issues

Delivery (Mechanical) Issues

[redacted]

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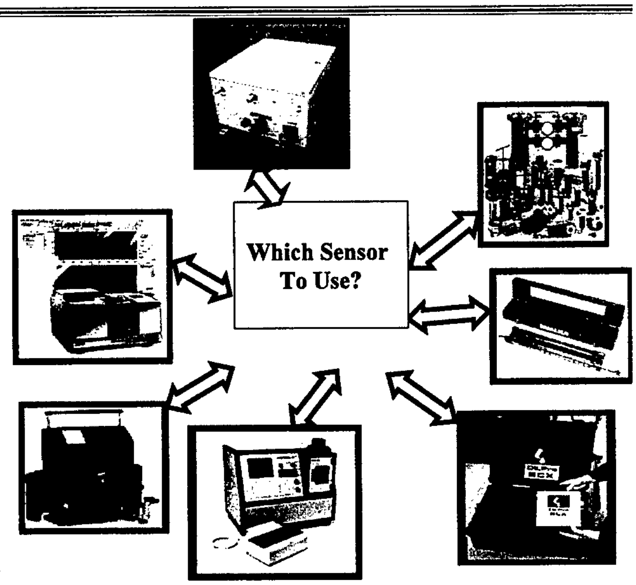
Oil Sensor Selection for Application



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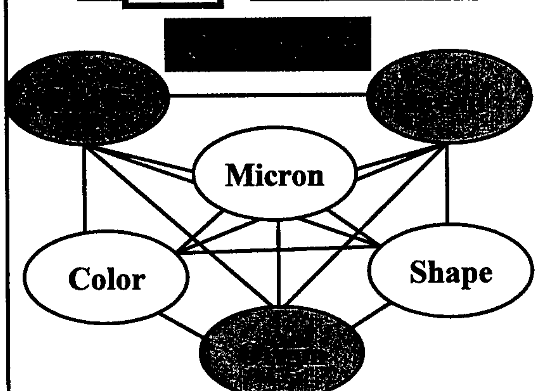
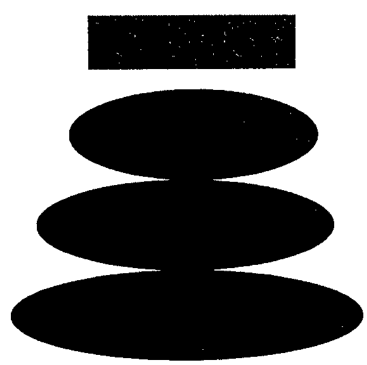
Oil Monitoring Choices





- Looking for a single debris result or a combination?
- Will the sensor present the data in desired format?

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Oil and Vibration Data Fusion For Assessing Machine Condition

Problems/Conditions	Oil Analysis	Vibration Analysis	Correlation
Thrust/Journal/Roller Bearings	Strength	Mixed	Wear debris will generate in the oil prior to a rub or looseness condition.
Misalignment	Not applicable	Strength	Vibration program can detect a misalignment condition. Lube analysis will eventually see the effect of increased/improper bearing load.
Oil Lubricated Antifriction Bearings	Strength	Strength	Lube program will detect/can detect an infant failure condition. Vibration provides strong late failure state information.
Shaft Cracks	Not applicable	Strength	Vibration analysis can be very effective in monitoring a cracked shaft.
Gear Wear	Strength	Strength	Vibration techniques can predict which gear. Lube analysis can predict the type of failure mode.
Root Cause Analysis	Strength	Strength	Best when both programs work together.

- **One is often a strong/ early indicator**
- **One indicates a fault while the other shows no change**

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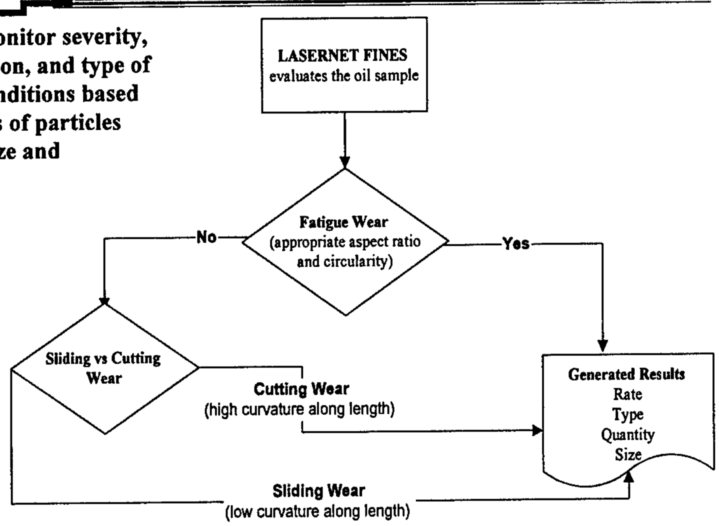
Initial Evaluation of Lasernet Fines

The goal is to monitor severity, rate of progression, and type of specific wear conditions based on the quantities of particles with different size and morphology.



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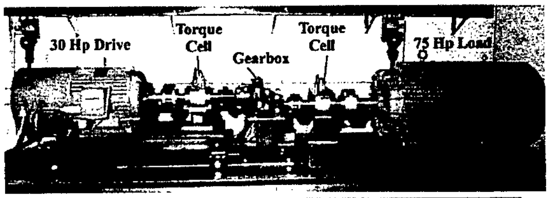
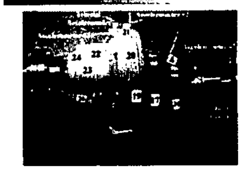
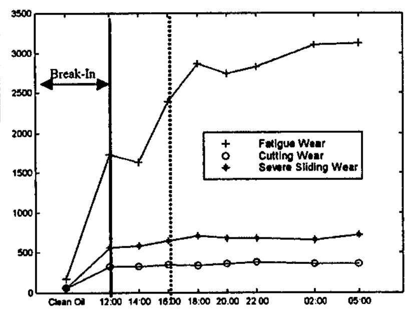
Lasernet Fines Results on MDTB





Front View

Back View



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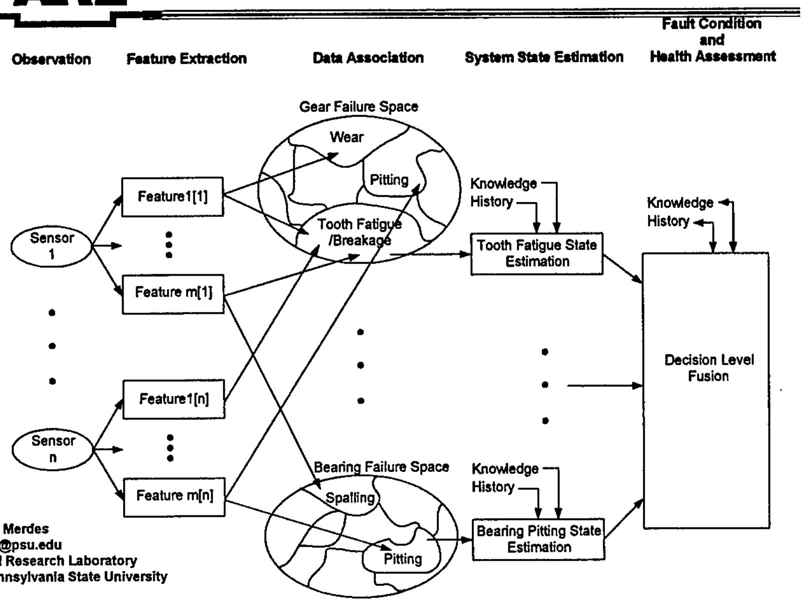
Vibration & Oil Data Fusion



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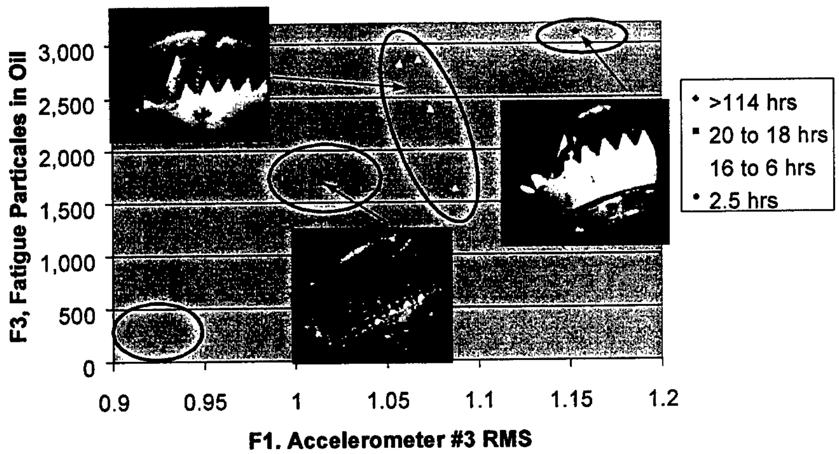
Non-commensurate Feature Classification



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Initial Evaluation Criteria

- Vendor
- Product/Capability
- Type (Off-Line, In-Line)
- Underlying Technology
- Features
- Development Status
- Costs
- Comments
- Positives/Negatives
- Merit Ranking (10=high, 0=low)
- Ranking Rational

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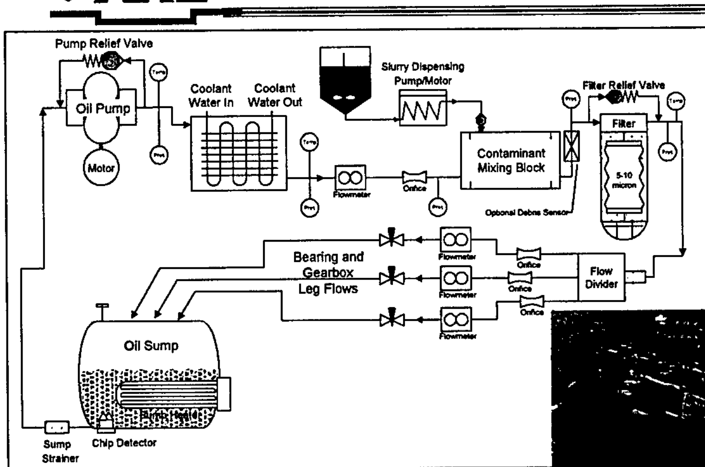
Lubrication System Test Bench



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LSTB Description

1. Replicates gas turbine engine lubrication system.
2. Used to develop validated model-based diagnostic approaches.
3. As in all pressurized lubrication systems – main pump draws flow from sump.
4. Lubrication oil flow rate is acceptable to gas turbine speed ranges, typically 60-100% of full flow.
5. Engine oil is usually cooled by air, fuel, or water based coolants.
6. Flow resistance of the individual cooling legs are modeled by fixed orifice in-line with variable throttle valves.
   ⇒ To model leg imbalanced due to bearing heating and normal variations between different engine types.
5. Oil is re-circulated to the sump and immersion heater is used to regulate bulk fluid temperature.
6. Simulate or produce lubricant
   - ⇒ Degradation
   - ⇒ Flow blockage
   - ⇒ Contamination
   - ⇒ Leakage
   - ⇒ Internally/externally generated debris

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"Honest Broker"

ARL proposes to be the "honest broker" by evaluating oil sensors under a variety of types of oil, with a variety of conditions.

Bottom line – how do these sensors perform and what are the limitations?

A test rig would be built and managed at the ARL for the testing of the sensor.

Sensors would be supplied for a predetermined amount of time for testing.
Observers would be welcomed.

ARL has the expertise required to build the test platform, but lacks a solid knowledge for assessing complex oil samples.

A team approach with a variety of interested oil laboratories along with the Joint Oil Analysis Program would prove beneficial.

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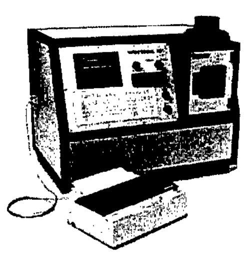
Spectroil M Oil Analysis Spectrometer

For the Analysis of Wear Metals, Contaminants, and Additives in Lubricants or Gas Turbine Fuels



- Detect potential problems
- Predict failures before they occur
- Avoid costly repair bills
- Reduce maintenance costs
- Cut expensive downtime

Remaining Oil Laboratory Components

Viscolab 3000

Lasernet Fines

Bichromatic Microscope

Bio-Rad Digital Oil Analyzer

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ACI Architecture, Algorithms, and Hardware

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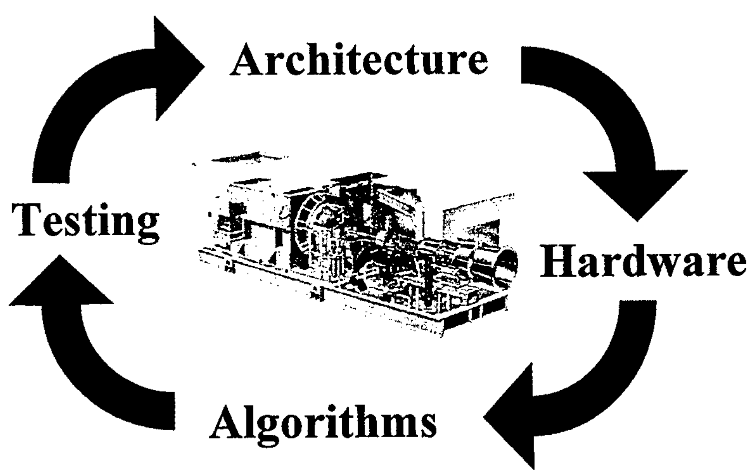
Voice: (814) 863-7671, E-mail: kmr5@psu.edu

Approach

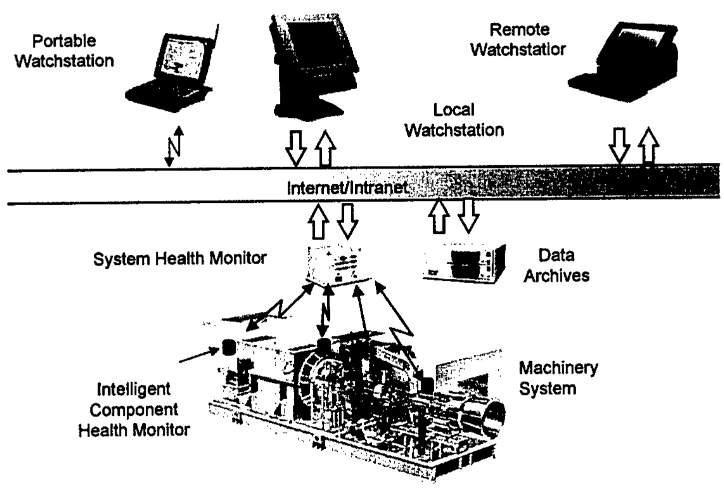


ACI Development Summary

- Demonstrated ICHM and SHM layers of 3-layer architecture for machinery health monitoring
- Developed and demonstrated brassboard ICHM hardware
- Developed new advanced algorithms for machinery diagnostics and prognostics
- Machinery focus on bearings, gears, and electrical generators
- Algorithms and system tested on MDTB and targeted at SSGTG

July 20, 2000 ACI Program Review 3

System Architecture



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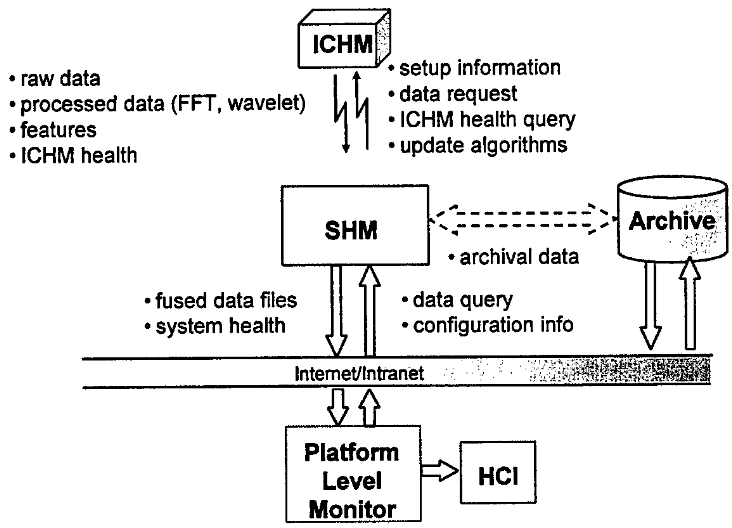
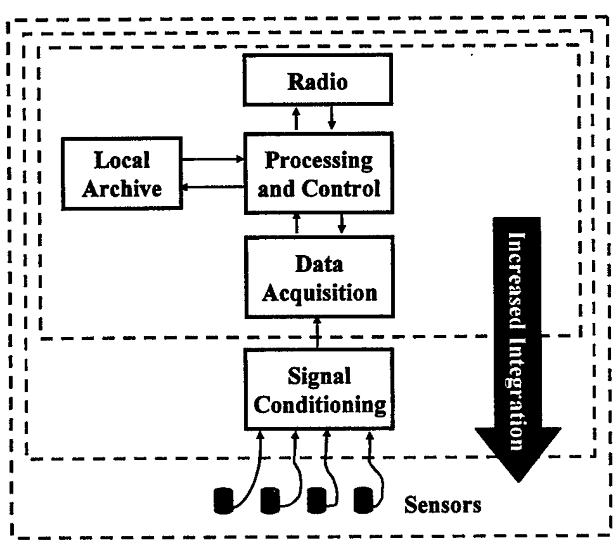
Information Flow



ICHM Hardware Functionality



ICHM Software Functionality

- Provides component health information
- Acquires and processes data
- Wireless connection to SHM
- Tracks changes in features
- Capable of autonomous or on-demand operation
- Provides time-series or spectral data on-demand to SHM

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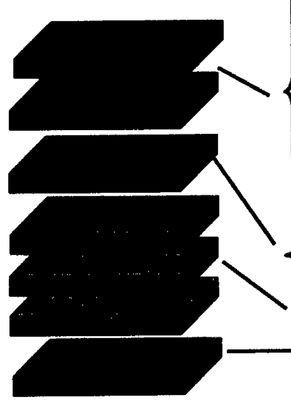
Modular ICHM Hardware Design



- Handles all radio communications
- Setup DACMs, and download executable code and parameters to DDPM
- Control DACM data acquisition: acquire data, demux DACM data, and store in memory for access by DDPM
- Maintain clock synchronized with SHM
- Maintain timer for DDPM sleep mode
- Control ICHM deep sleep mode

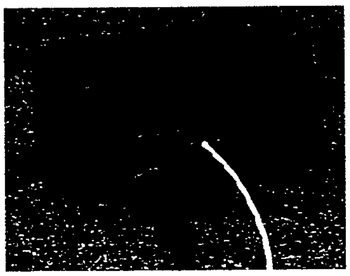
- Process data from DACM's
- Compute features, perform data fusion and classification
- Generate alert messages and health reports

- Acquire data on command from DDPM

- Provide power and control power usage

July 20, 2000 ACI Program Review 8

ACI ICHM Hardware



IVC ICHM Hardware Specifications

PARAMETER	VALUE	UNITS
Resolution	16	Bits
Input Range	±4.5	Volts
Input Type	Single-Ended	-
Maximum Sample Rate / Channel	195.2	KHz
Minimum Sample Rate / Channel	5.96	Hz
8 Pole Bessel Filter (-3dB)	25(1)	KHz
Programmable Gain	1,2,4,8	Volts/Volt
Offset Range	±4.5	Volts
Excitation	0.40 – 0.63 (0.515 Typical)	mA (Constant Current)
Size (including housing)	5.44 x 3.51 x 0.47	Inches
Power (7.0 Volts)	185	mA
Weight	6.0	Ounce (oz.)

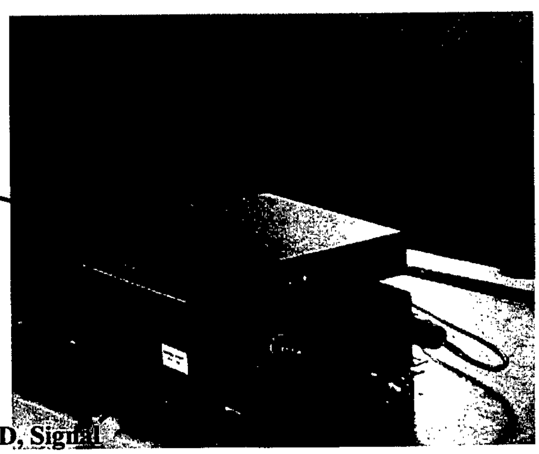
NOTE (1) – MAY BE FACTORY SET 10kHz to 50 KHz

IVC ICHM Hardware Capability

- Node-to-node synchronization desireable, but multi-channel capability means synchronization not absolutely necessary
- Node-to-node synch important for commensurate sensor fusion at SHM
- 16-channel capability useful for wireless data collection
- 16-bit, 200 kHz A/D capability better than COTS at start of ACI, comparable to high-end now
- 24-bit A/D may be required in near future

OST ICHM™ 2000

2.4 GHz Radio



Processor, A/D, Signal Conditioning

OST ICHM™ 2000 Hardware

ICHM™ 2000 Hardware Capability

- 60 MIPS/120 Mflops processor
- 16 MB SDRAM / 8 MB Flash memory
- 2 dynamic vibe channels (96 kHz sample rate, 24 bit)
- 4 low-speed channels for temperature and pressure
- Integrated sensor excitation and signal conditioning
- Excitation monitoring for sensor health assessment
- Internal temperature monitoring
- Tach digital input
- Highly synchronizable

Current Efforts

- Algorithm implementation on OST ICHM™ 2000 and COTS (PC-104) hardware platforms
- RS232 communication via COTS 2.4 GHz wireless modem (Bluetooth to follow shortly)
- Comparison of hardware dynamic range effects on PSU testbeds using different hardware platforms (August 2000)

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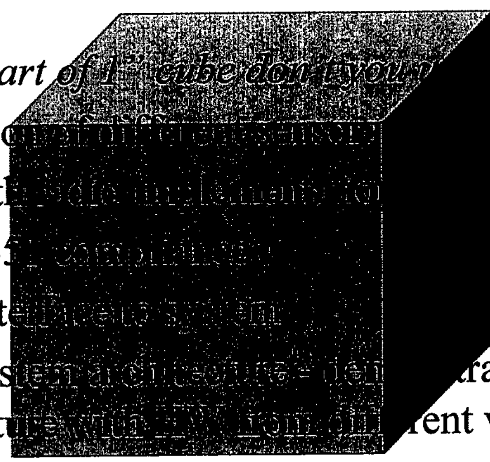
Future HW Efforts

- "*What part* … *rstand?* "
- Integrati…
- Bluetoot…
- IEEE 14…
- XML int…
- Open sys… …rate architect… …ent vendors



2.54 cm x 2.54 cm x 2.54 cm

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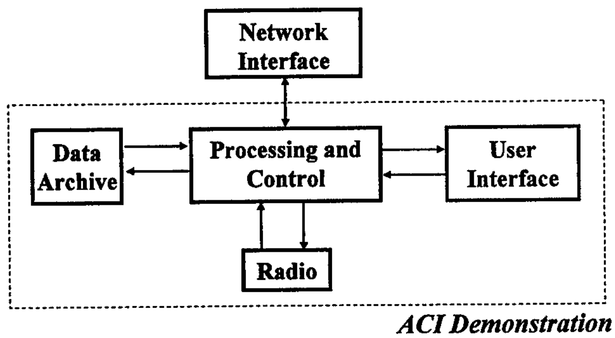
SHM Hardware Functionality



SHM Software Functionality

- Controls operation of ICHMs
- Request data from ICHMs
- Wireless interface to ICHMs
- Performs feature-level data fusion and pattern recognition
- Provides system health information
- Network interface to internet or intranet
- Maintain database of system health information

Implemented SHM Software Functionality

- Controls operation of ICHMs
- Request data from ICHMs
- Wireless interface to ICHMs
- ~~Performs feature-level data fusion and pattern recognition~~
- Provides system health information
- ~~Network interface to internet or intranet~~
- ~~Maintain database of system health information~~
- Provide user interface (*ACI Demonstration*)

ACI Demonstration Software

- Demonstrate SHM and ICHM layers of HMS architecture developed under the ACI
- Demonstrate operation of ICHM
  - Unattended data acquisition and processing
  - Generation of component health information
  - Scripting of ICHM commands to change analysis routines
- Graphical user interface at SHM combines SHM and PLM functionality

ACI Software Development

SHM

- ICHM scheduler software
  - ICHM setup
  - ICHM algorithm scripting
  - Data request
- Demo GUI

ICHM

- Task manager
- Data acquisition
- Low-level embedded system software
- Basic analysis routines
- Advanced analysis routines

ICHM Task Scripting

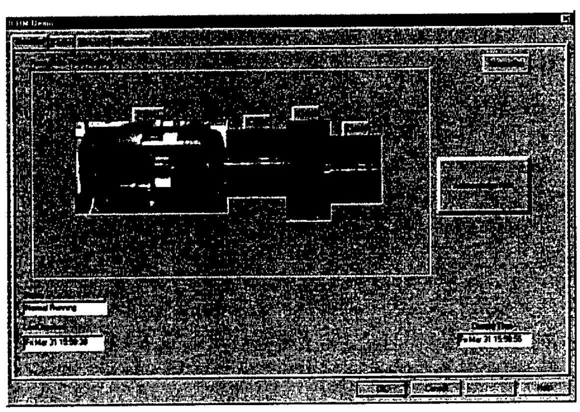
- Provides method of "programming" ICHM without downloading new executable
- ICHM functions or operations are scripted together at the SHM in the form of a task list
- Each task corresponds to a function call on the ICHM
- Task lists may be executed once or many times
- Java provides an alternative approach but requires JVM or RTOS on ICHM

ICHM Task Scripting

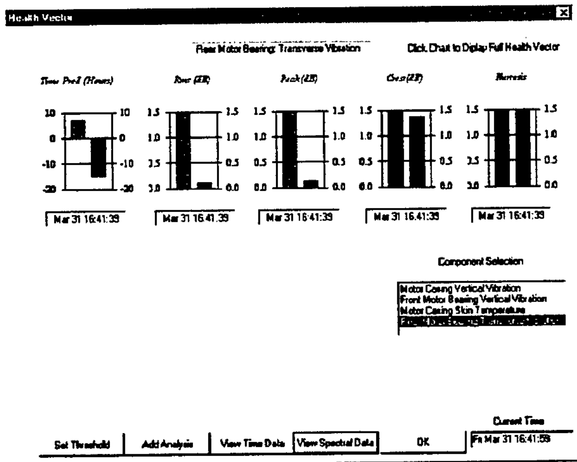
- Example task list:

1. Set measurement bandwidth;
2. Set channel gains;
3. Set data buffer length;
4. Acquire data;
5. Compute basic signal features;
6. Compute FFT;
7. Update power spectrum estimate;
8. Compute remaining useful life for each feature;
9. Generate health vectors.

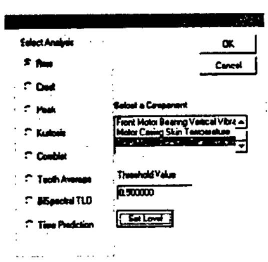
ACI Demonstration Software
- *Example Screens*

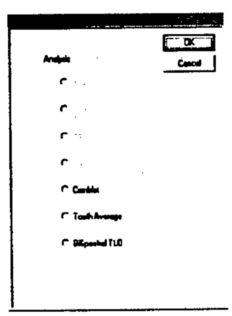


ACI Demonstration Software
- *Example Screens*



ACI Demonstration Software
- *Example Screens*





Thresholds can be set for each analysis feature for each monitored component

ACI Algorithm Development

- ICHM algorithm development
  - RPI
  - PSU
  - Barron associates
  - Logicon
  - BBN

  (RPI, PSU, Barron associates, Logicon, BBN): **Bearings and gears**

  - University of Kentucky — **Electrical generator**
- Algorithm Measures of Effectiveness and Measures of Performance
  - Tennessee State University

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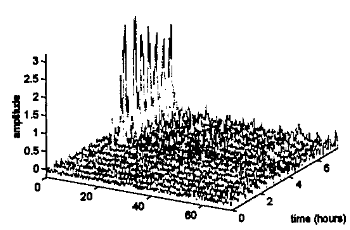
ACI Software Development – *Comblet Processing*

- Wavelet characteristics chosen to implement narrow bandwidth bandpass filters
- Comb filters based on wavelet basis functions (comblets) are constructed to remove the residual error signal from measured gear vibration data



- The kurtosis of the residual error signal gives early detection of gear damage

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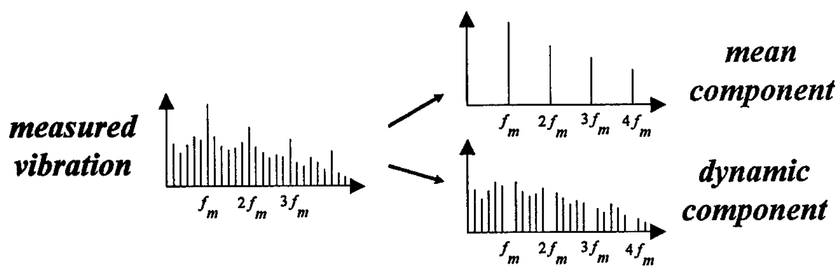
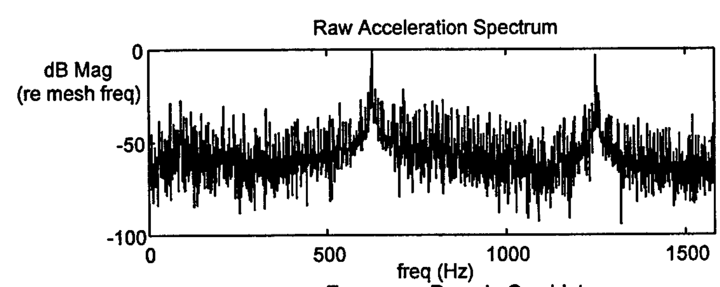
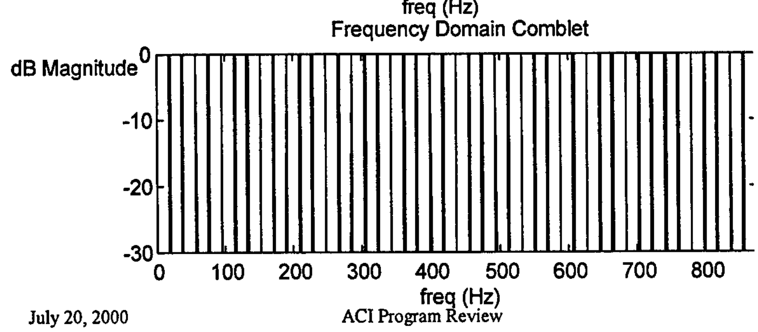
Gear Vibration Sources

- Static or nominal surface imperfections and elastic tooth deformations
  ➡ gear mesh frequency and harmonics
- Dynamic component of surface imperfections
  ➡ remaining harmonics and sidebands

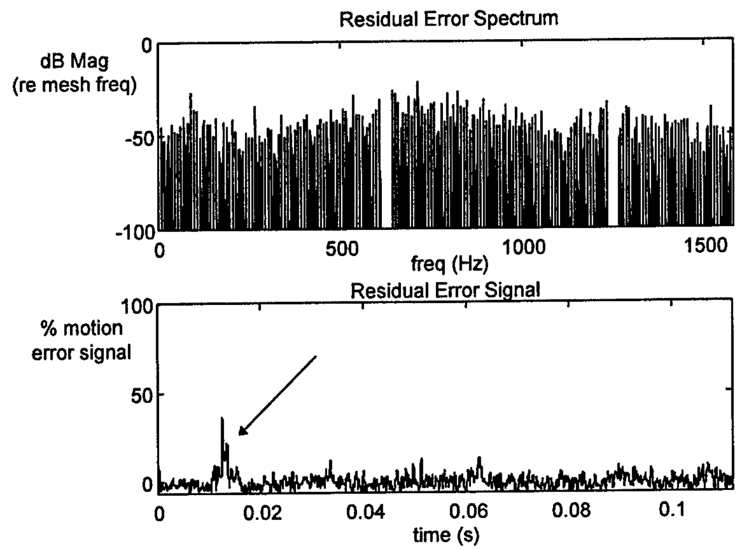


ACI Software Development
– *Comblet Processing*





ACI Software Development
– *Comblet Processing*



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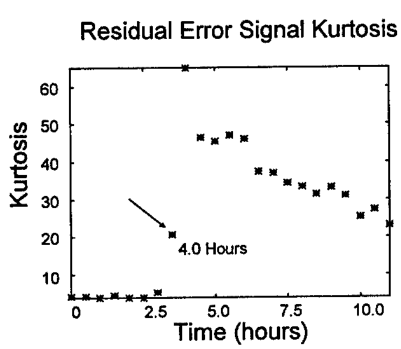
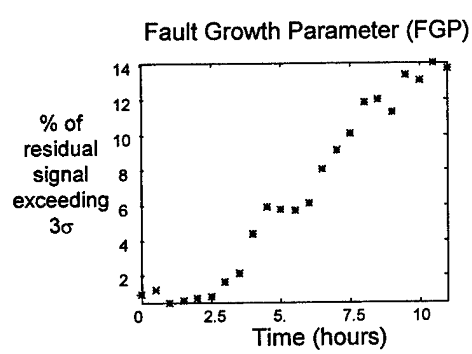
Health Prognosis





Diagnosis → **Prognosis**

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ACI Algorithm Development
– *Tooth Averaging Algorithm*

- Averages gear vibration from one tooth mesh to the next over a complete revolution of the gear.

$$\bar{x}(n) = \frac{1}{M}\sum_{j=1}^{M} x_j(n)$$

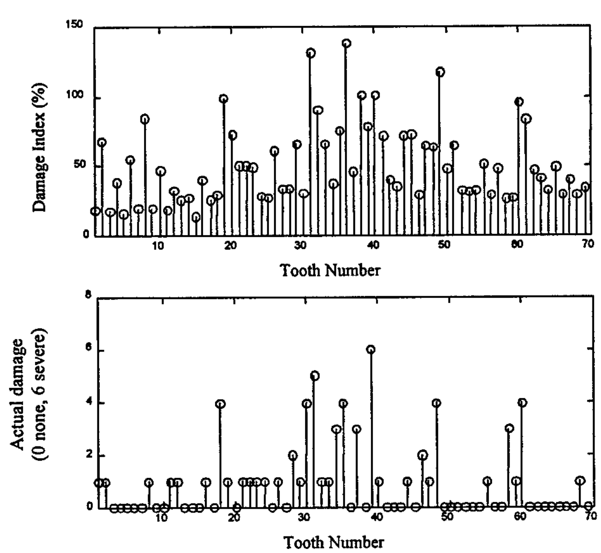
$x_j(n)$ represents the gear vibration sequence while the j^{th} tooth is in mesh and there are M teeth in the gear

- Average represents normal meshing dynamics of all the teeth

$$e_j(n) = x_j(n) - \bar{x}(n)$$

- Difference between the vibration of a tooth and the average tells how different the tooth is from the norm - magnitude gives an indication of how abnormal the tooth is due to localized faults
- Sources of difference include localized tooth faults such as pitting or crack.

ACI Algorithm Development
– *Tooth Averaging Algorithm*



ACI Algorithm Development
– *SECZ Algorithm*

- Algorithm consists of a demodulator and classifier
- Demodulator determines if the bearing vibration is amplitude and/or frequency modulated at the bearing characteristic defect frequencies, and estimates the strength of modulation signals
- Classifier determines severity and if the problem warrants a warning
- Example output:

Feat. 1	**Feat. 2**	**Freq.**	**Conf.**
0.466912	**0.020789**	**119.047619**	**4.136034**

Bad Bearing-Damaged in Outer Race
This is how confident I am 4.136034

ACI Algorithm Development
– *Bispectral TLO*

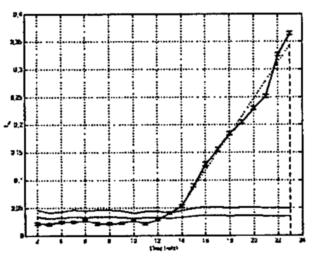
- Bispectral statistical data are used to detect faults, estimate fault severity, compute remaining useful life (RUL) and confidence in RUL estimate.
- Bispectrum is used to detect nonlinear phase coupling between different frequencies.

$$B_k(f_1, f_2) = X_k(f_1)X_k(f_2)X_k^*(f_1 + f_2)$$

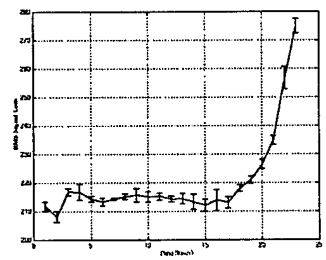
- Reveals additional information about phase coupling between different defect frequencies in measured vibration signals compared to typical power spectrum analysis, higher-order statistics and spectra.
- Statistical change detection detects localized bispectral energy changes indicative of damage progression in components
- Does not need a priori knowledge of the signal statistics

ACI Algorithm Development
– Bispectral TLO

- *Non-seeded* CH-47D helicopter transmission spiral bevel input pinion gear tooth bending fatigue failure during test cell overloading (156%)



Bicoherence-Based Statistic, T_N, vs. Time, t, with 5σ and 10σ Confidence Lines. (Dotted line indicates linear fit of data over $13 \leq t \leq 23$ minutes.)

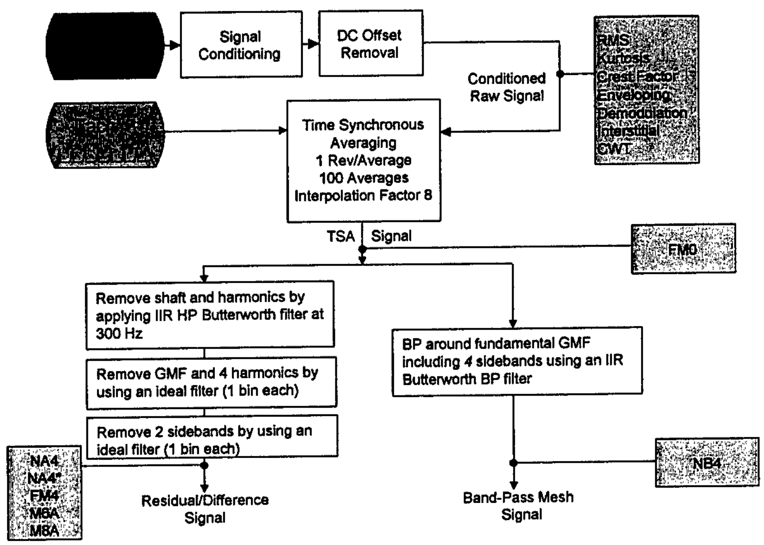


RMS Vibration Levels, Indicating the Substantial Reduction in Detection Delay Afforded by the Bispectral-Based Statistic, T_N, which Detects the Fault at t = 13 min.

ACI Algorithm Development
Electrical Generator Diagnostics

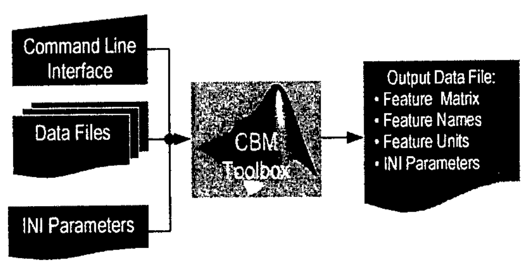
- Algorithm computes FFT of each input channel, retaining the amplitude and phase angle
- 60-Hz components are used to compute the general performance parameters of the generator: line voltage, line current, output power
- Deterioration detectors are computed from specific combinations of the transformed values
- Changes (compared with the "normal" values) in these detectors indicate a specific type of deterioration or failure

*Optimal** Preprocessing Flow



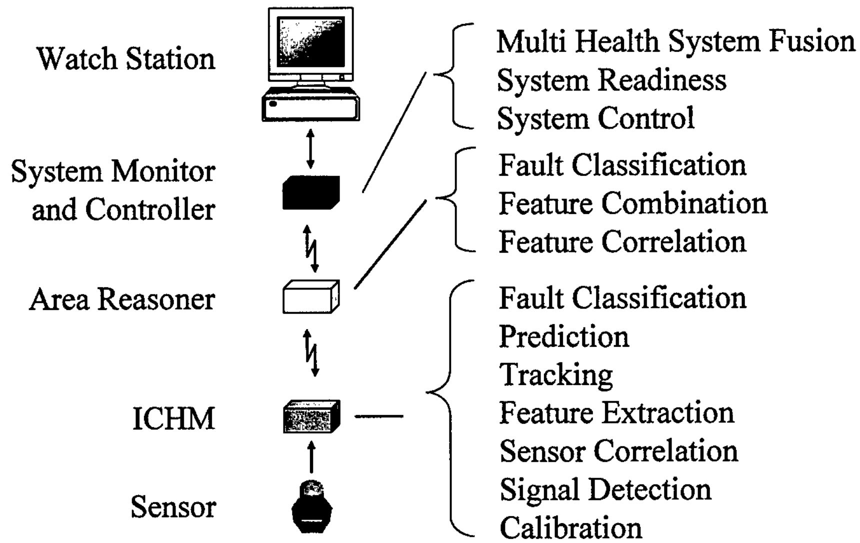
*Optimal for MDTB Accelerometer data

CBM Features Toolbox

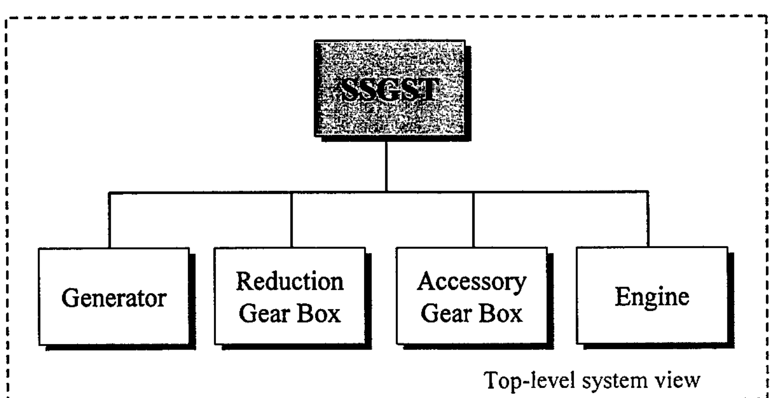


- Standard way to share algorithms and results - eliminating confusion:
  - Gearbox, sensor, preprocessing parameters, etc. are saved *with* the FOM data
  - Feature names and units are saved along with the FOM data
- Straightforward Interface
- Easily expandable for new features
- Simplistic input and output file structure
- Allows batch processing of features and data
  - *One* Matlab command processes desired features and sensor data!

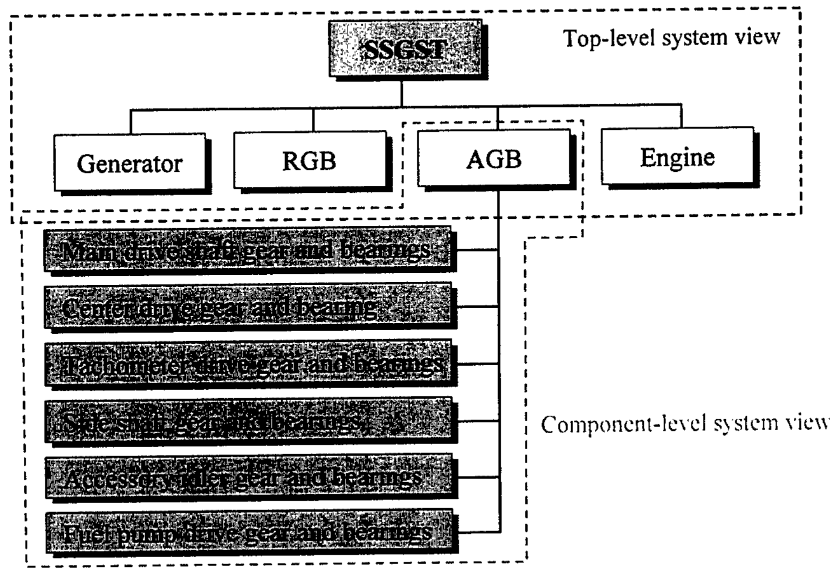
MHMS Data Processing and Fusion



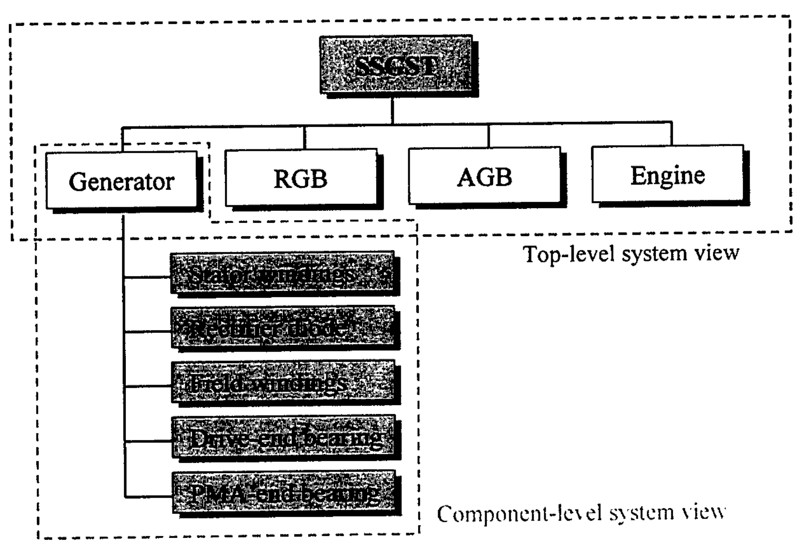
SSGTG Machinery HMS Subsystems



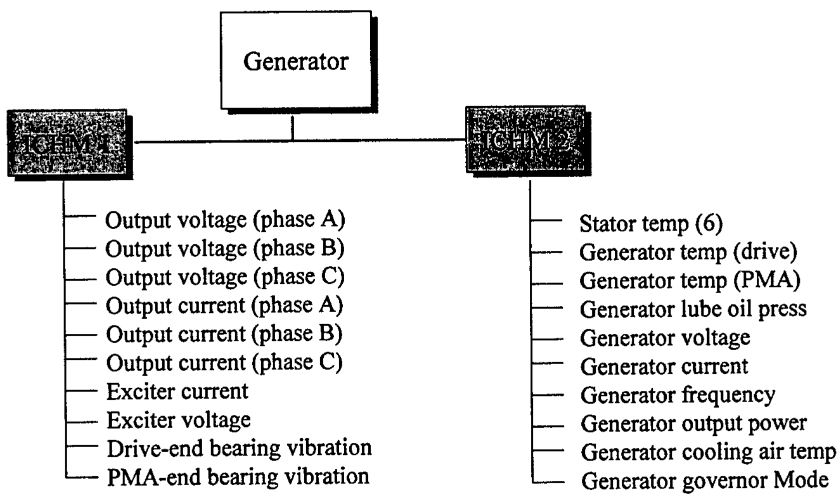
SSGTG AGB Components



SSGTG Generator Components



Generator ICHM Inputs



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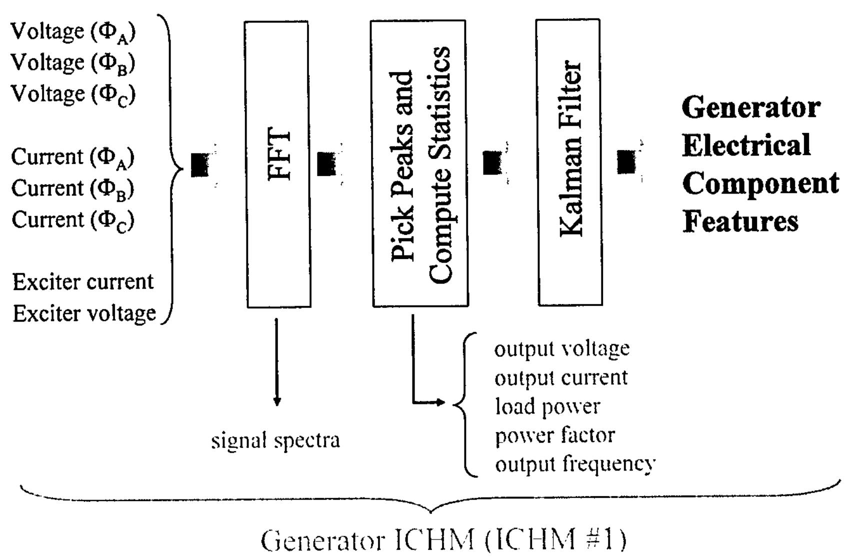
Electrical Generator Health Monitoring



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Electrical Generator Health Monitoring

Generator Electrical Component Features → Decision Logic →

Thresholds and Tolerances ↑ (into Decision Logic)

Generator Electrical Faults

- Stator winding deterioration (including turn-to-turn, coil-to-coil, and phase-to-phase)
- Rectifier diode failure
- Field deterioration
- Operating parameters out of limits (voltage, current, power factor, frequency, etc.)

Generator ICHM (ICHM #1)

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Generator Status Monitoring

Generator voltage
Generator current
Generator frequency
Generator output power
Generator governor Mode
Stator temp (6)
Generator temp (drive)
Generator temp (PMA)
Generator lube oil press
Generator cooling air temp

→ Compute Statistics → Kalman Filter → Smoothed and predicted signal values

Generator ICHM (ICHM #2)

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Electrical Generator Health Monitoring at SHM Level

Stator winding fault (ICHM 1)
Stator temp meas. (ICHM2)

- Increase or decrease confidence in stator winding fault

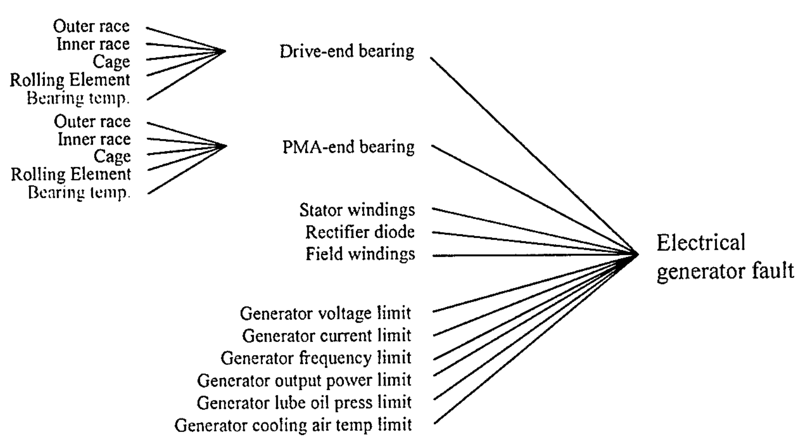
Generator operating parameters (voltage, current, power, freq.) from ICHM1
Generator operating parameters (voltage, current, power, freq.) from ICHM2

- Increase or decrease confidence in out-of-operational limit faults
- Identify sensor problems

Bearing faults (ICHM 1)
Bearing temp (ICHM2)

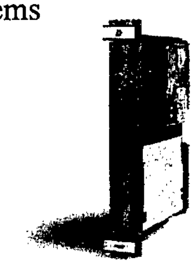
- Increase or decrease confidence in bearing fault

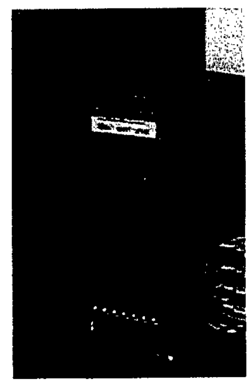
Electrical Generator Fault Tree



New Initiatives:
CBM and Controller Integration

- Many signals of interest for machinery health monitoring already exist in control systems
- Need to integrate CBM system and access signals without affecting existing control systems
- Leverage from developments in IMATE program





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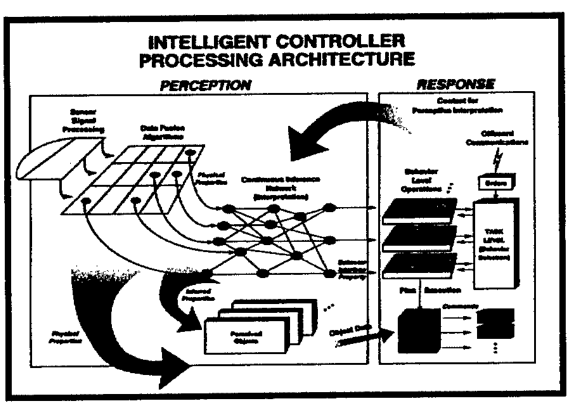
New Initiatives:
Combine Monitoring and Control



Combination of ARL Core Competencies

Intelligent Response Capability for Machine Monitoring

<u>Merged Capabilitities</u>

- Machine monitoring technologies
- Intelligent sensor information
- PIC perception, integration, and inferencing
- PIC response for automated failure prevention and prognostics

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ACI Development Summary

- Demonstrated ICHM and SHM layers of 3-layer architecture for machinery health monitoring
- Developed and demonstrated brassboard ICHM hardware
- Developed new advanced algorithms for machinery diagnostics and prognostics
- Machinery focus on bearings, gears, and electrical generators
- Algorithms and system tested on MDTB and targeted at SSGTG

Future Directions

- Continue four-point effort to develop and implement health prognostics
- Transition CBM from laboratory to test-beds to the fleet
- Emphasize system level fusion, area reasoning and prognostics
- Integrate machinery health prognostics and control
- Maintain OSA-CBM compliant approach to machinery health prognostics

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ARL

Condition-Based Maintenance

Prepared for:

ACI RCM Workshop

Presented by:

Bill Nickerson

Head, Condition-Based Maintenance Department

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State College, PA 16804-0030
814-863-9899/gwn1@psu.edu

Bill Nickerson is the Head of the Condition-Based maintenance Department at Penn State Applied Research Laboratory. He joined ARL in 1993 after working for the Navy at the David Taylor Research Center in Annapolis, MD for 15 years.

His background is in shipboard auxiliary machinery design and development and condition-based maintenance research. He has been active in developing the research program at the Office of Naval Research from its inception as a Logistics Block Program project in the late 80's.

The CBM Department at ARL is responsible for a variety of programs ranging from basic research through application in a variety of platforms from ships to amphibious vehicles to rotary wing to fixed-wing aircraft.

Bill holds a B.S. in Civil Engineering from Penn State and two Master's of Science in Engineering degrees from the University of Michigan in Mechanical Engineering and Naval Architecture & Marine Engineering.

“Preventive Maintenance
Doesn’t
(prevent maintenance)”

MGEN Mike Williams, USMC
Commander, MARCORSYSCOM
21 August 1996

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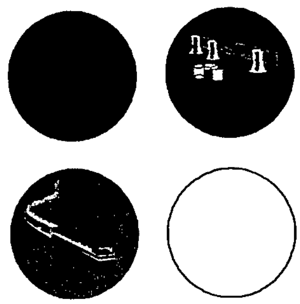
This one statement explains one of the major motivators for maintaining equipment on-condition.

MGEN Williams said this on a visit to Penn State ARL in August 1996. He referred to the frequency with which we make matters worse in undertaking preventive maintenance actions in the discussion that followed this quote.

One major benefit of NOT doing time-directed preventive maintenance is avoiding the problem or “maintenance-induced failures”. Numbers as high as 80% have been quoted as the fraction of total failures attributable to mis-assembly or damage during a preventive maintenance action. Clearly the best thing you can do for a machine that is running well is to leave it alone. Thus, the reasoning to “continuously” monitor the health of operating equipment and base maintenance decisions on a concrete indication of impending failure.

Condition-Based Maintenance Thrust



Objective -

Enhance operational effectiveness and safety through research and development of the technologies to accurately and reliably predict the *remaining useful life* of equipment in service for Navy, Tri-Service and dual-use applications

Approach -

- Develop a vertically integrated program Basic Research to Platform-Level Demonstration
- Link tightly with industry partners from the outset

Payoff -

- Increased Operational Availability
- Reduced Maintenance Costs
- Increased Safety of Operations
- Improved Mission Assurance

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The overall objective of the work is to move "maintenance" from the logistics time frame (longer term planning) and move it into the operational time frame where real decisions about which equipment to employ are based on realistic and reliable measures of that equipment's health and likelihood of completing the assigned mission.

This capability would have significant impact on operational decisions, safety, and also reduce maintenance expenditures dramatically.

Achieving this objective will require basic research into the "science of failure" and a concurrent engineering approach to development that involves the equipment manufacturer from the outset.

This technology is inherently "dual-use". Maintenance problems in the military are no different from those in the commercial sector. Both have missions to complete whether that is transporting troops across the beach or delivering a time-critical shipment of automobile parts to a "just-in-time" manufacturing line in Detroit. Failure during the course of a mission is unacceptable.

Reliability Centered Maintenance

- Process for defining the maintenance requirements of equipment systems - IT IS NOT A MAINTENANCE PHILOSOPHY!
- Steps in RCM:
  - Hierarchical decomposition (functional) of plant
  - List functions with performance expectations
  - For functions, describe all ways the asset can fail
  - Describe ways in which mode manifests itself
  - Apply "RCM Logic" to categorize consequences and identify recommend maintenance action

From GasTOPS CaseFILE December, 1995, M. Tobin

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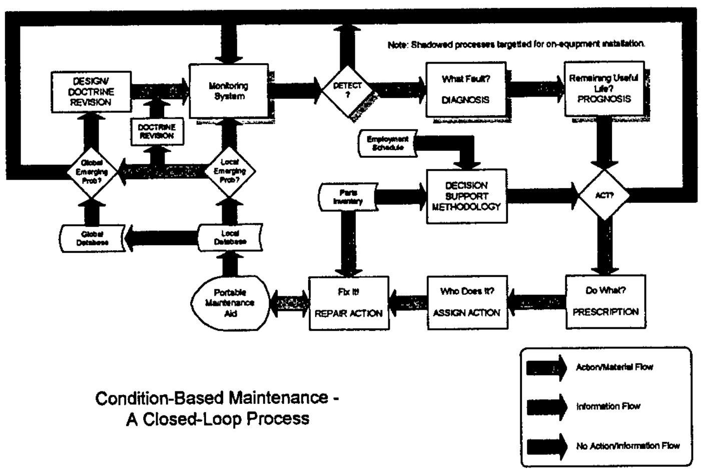
Reliability-Centered Maintenance was developed by United Airlines working with the FAA and Boeing aircraft in the late 60's to address the problem with scaling maintenance practices from previous aircraft to the wide bodies entering the fleet. A rigorous process was required to base maintenance decisions and practices on a rational basis. The concept of "applicable and effective maintenance actions" evolved.

RCM is not in itself a maintenance philosophy, it is a process to determine the proper combination of time-directed, corrective, and condition-directed maintenance tasks in your maintenance program. Frequently, maintenance programs developed using RCM processes are characterized as RCM, but this is an improper use of the term as originally described.

The steps in an RCM analysis shown will result in a practical and rationally justified maintenance program. The problem with traditional RCM is that it was designed long before the advent of the computer and communication technology available today.

Part of our program is targeted to update the RCM process to enable the decision to move to a condition-based maintenance program for the majority of equipment items to be made more rationally using the latest practical technologies. The general steps of the RCM process apply, it just requires altering the weighting factors at decision points.

CBM is a Closed-Loop Process



Condition-Based Maintenance - A Closed-Loop Process

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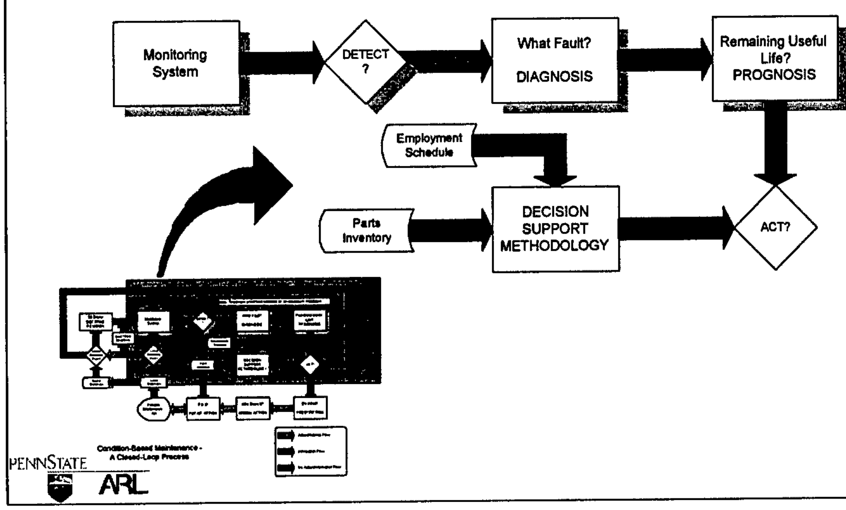
Condition-Based Maintenance as we describe it is a closed-loop process encompassing the entire operational cycle of a system.

The process starts with monitoring (including human observation) a system to first detect an incipient fault, diagnose what the fault is, predict the remaining useful life of the equipment item and support a decision to act. These items represent the key elements of mechanical diagnostics and is explained in more detail elsewhere.

Important other parts of this process include deciding what action to take (prescription), assignment of the human resources to take the action, executing the necessary action, capturing the knowledge gained during the action, distributing that to local and global databases, and monitoring locally for indications of a systemic problem that can be addressed by local actions (e.g., personnel training) and globally for indications of population-wide problems which are best corrected by a design change or doctrine change.

An example of a global problem might be a batch of bearings that were of inferior quality but escaped detection until after installed. At the time the problem is discovered, it might be necessary to replace all the bearings in service. Without seamless capture of data during the repair process and a good logistics database, it would be impossible to identify this type of problem and very difficult to implement a repair without wholesale replacement of the suspect part.

Mechanical Diagnostics Focuses on a Part of the Problem



Our activities in mechanical diagnostics and prognostics focus on only one part of the overall CBM process: Monitoring, Detection, Diagnosis, Prognosis, and the Decision to Act. These processes must occur serially in the order shown, though they may appear at times to be simultaneous.

The basis of this assertion is the hypothesis that all machines are progressing during their operation along several lifelines that will ultimately lead to failure. Until a fault initiates (probably at the microscopic level, and initially undetectable) there is no basis from which to predict the time to failure other than a statistical method based on a population of like machines. During that time, monitoring continues using all the capabilities available including human observation.

When a detection is made, i.e., an observable feature exceeds an acceptable threshold, the diagnosis process is started to determine the nature of the incipient fault. This step could be very simple based on the observed exceedence or it could require interrogation of the system or analysis of a combination of observable features.

Once the diagnosis is made, it is possible to start making predictions of the remaining useful life of the system. This process requires a prediction of the evolution of the fault in the context of future operational loads and will improve in precision and confidence as the machine continues to fail.

When the confidence is sufficient to warrant operator attention (with or without "man-in-the-loop" control) a decision support process is initiated. This process considers near-term employment schedules and resources available to affect the necessary repair. Both of these can alter a decision on when to take action. It is, of course, necessary to account for the decision to take no action and continue monitoring the evolution of the fault.

A Framework for CBM

- Offers a set of definitions - A "Glossary"
- Facilitates Communication of the concept
- Defines "How Well" We Need to Predict the Future to Make a Difference
- Prescribes the Research Agenda

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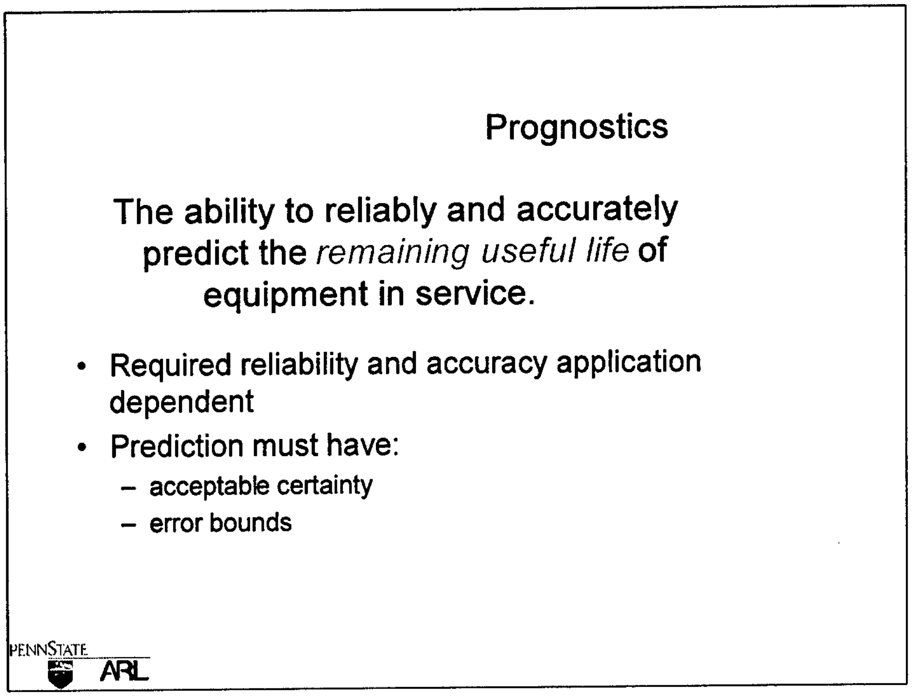
In order to undertake this research program, we had to develop a framework for communication among ourselves. The field has no established lexicon and, as a result, terms are used with different meanings. For example, a statement that this equipment is going to fail is sometimes called a prognosis or prediction. If that is truly a prognosis, I can be correct in 100% of my predictions - all machines will fail if operated long enough. The issue is knowing when the particular machine will fail, precisely enough and with sufficient confidence to warrant action by the equipment owner.

We've tried to clarify our communications by establishing definitions of the terms as we use them and to be consistent in our use of the terms. We feel it is important to do this to ensure that we accurately communicate our intentions and results.

This framework also allows us to define how well the technology must work to be useful in service. Without asking this question, the investment in research and development will without doubt be misapplied and successful implementation will be delayed.



Prognostics is probably the most mis-used term in the area of condition-based maintenance. It is frequently determined by trending a particular (or combination of) parameter(s). The result is usually presented as a prediction that the machine will fail, presumably in the near future. Unfortunately, this is insufficient to warrant on the part of an owner (represented by an operator).

One must understand that remaining useful life is the important concept. Failure is too dependent on the application, e.g., a submarine bearing is failed if it is noisy, not so in a paper mill.

A prediction or prognosis must include error bounds around its expected value of prediction and must explicitly achieve an acceptable level of certainty.

Unfortunately for the researcher, these are decisions that must be make according to the application and by the owner. The researcher can only respond by developing technology that meets the requirement or identifying research needs in areas that require improvement to meet the requirement.

End of Useful Life

That point in the failure evolution of a
machine
at which its owner would *choose not*
to start
the next *mission*
if the true condition of the machine
were known to her/him.

PENNSTATE ARL

In order to understand the concept of useful life, it is necessary to define the end of useful life.

It is important that this point in NOT failure in the normally understood sense of equipment being found unsuitable for the application during operation. It is rather a point where the machine is not predicted to continue satisfactory operation (defined by the owner) during the next (or an acceptable number of missions).

This is the point where the owner would not knowingly risk mission success on this equipment if he/she were able to accurately know the true condition of the machine.

Remaining Useful Life

- The operational time from the present until a system will not be able to successfully complete its next *"mission"* because it:
  - Won't be safe within acceptable confidence limits
  - Won't meet minimum tolerance levels
    - Noise (e.g., submarine bearings)
    - Dimensional accuracy of machined parts
    - Will operate below cost effective efficiency
    - Will fail catastrophically

PENNSTATE ARL

Remaining useful life is an operational time measure much more so than a calendar time. It is tied very closely with the concept of end of useful life where the owner would not knowingly undertake a mission because the required performance of the equipment will not be met and with an acceptable level of certainty, the equipment will jeopardize the mission's success.

It is important to note that there are any number of reasons a machine would not be able to successfully complete the next mission. It is not dependent only on a catastrophic failure, it could include a probability of failure that is unacceptable for the application based on objective evidence from the monitoring system.

Critical Prediction Horizon

- The time required by the operator to conveniently and/or safely take the required action for the particular failure trajectory.
- It is a function of:
  - Time between convenient repair opportunities (e.g. one mission)
  - The consequences of failure
  - The difficulty of the required action
- Defined as a constant times a number of repair opportunities

PENNSTATE ARL

Some points in the failure trajectory need to be established.

The critical prediction horizon is the point at which the owner defines he/she wished to be informed about an impending failure. It represents an integer number of missions that allow him to conveniently and safely plan and undertake the indicated action accounting for availability of resources, other influences like availability of back-up equipment, and lead-times for parts and scheduling.

Until the prognosis element predicts that the remaining useful life of the equipment is less than the number of missions required by the critical prediction horizon, the monitoring system will not inform the owner of the presence of an evolving fault, unless queried.

Critical Detection Horizon

- The time defined by the sum of the Critical Prediction Horizon and the time required to refine the projection of Remaining Useful Life to a sufficient confidence for the application.
- It is a function of:
  - Time to conduct analysis required to make prediction.
  - Consequences of a "Miss" and a "False Alarm"
- Defined as a constant times a number of Prediction Cycles

PENNSTATE ARL

Some points in the failure trajectory need to be established.

Critical detection horizon is much more applicable to the technology developer than to the owner. This time represents the amount of time required for the operator to take action(critical prediction horizon) and the amount of time it takes for the prognostic module to refine its prediction to an acceptable level of precision and confidence.

Prognosis will not likely be a one-time through process. It is expected to be iterative in nature, refining its estimate of remaining useful life after every iteration. It would be nice if the remaining useful life "clock" ran backwards at the same rate as the elapsed time on the equipment operations meter, but that is unlikely.

More likely, the system will make a prediction, monitor performance for a period of time, make another prediction, compare the results of the two predictions, and refine its prediction in an iterative process. As long as the time between detection and alert is sufficiently long to allow the prediction process to refine its prediction to an acceptable level, we can successfully implement CBM. If that time is not sufficient, we need to detect the incipient fault earlier or reduce the time our prediction requires to operate.

How Well Must We Do?

- Sensitivity Required for Detection is Defined by:
  - Time Required to Provide the Operator with Sufficient Warning (Critical Prediction Horizon):
  - Confidence in prediction high enough to warrant action
  - Enough repair opportunities to conveniently and safelytak action
  - Plus Time Required by the Analysis to Achieve the Necessary Level of Confidence in the Prediction
- Precision of Prediction Required is Defined by:
  - Risk (as Defined in Statistical Decision Theory) of False Alarm and/or Miss
  - Lower Risk Application Drives Higher Precision; Higher Risk, Lower Precision

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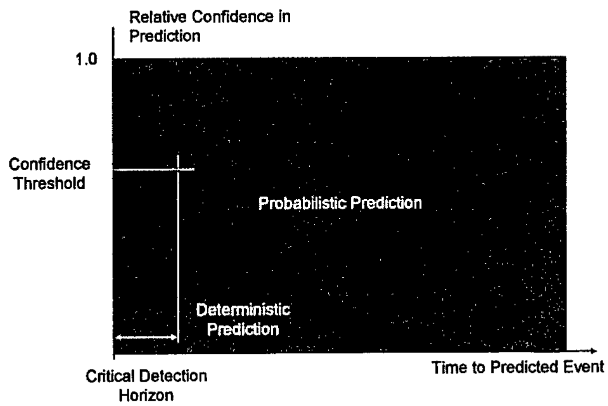
The definition of how well we must do comes from the owner of the equipment in question. It is important for us to understand this so that we can meet the requirements of the application. The system design should be such that adequate performance (that level that the owner is willing to pay for) is achieved, but the solution is not "gold-plated"

The above describe sensitivity and precision requirements to make a meaningful decision in the operational environment.

Predicting the Future



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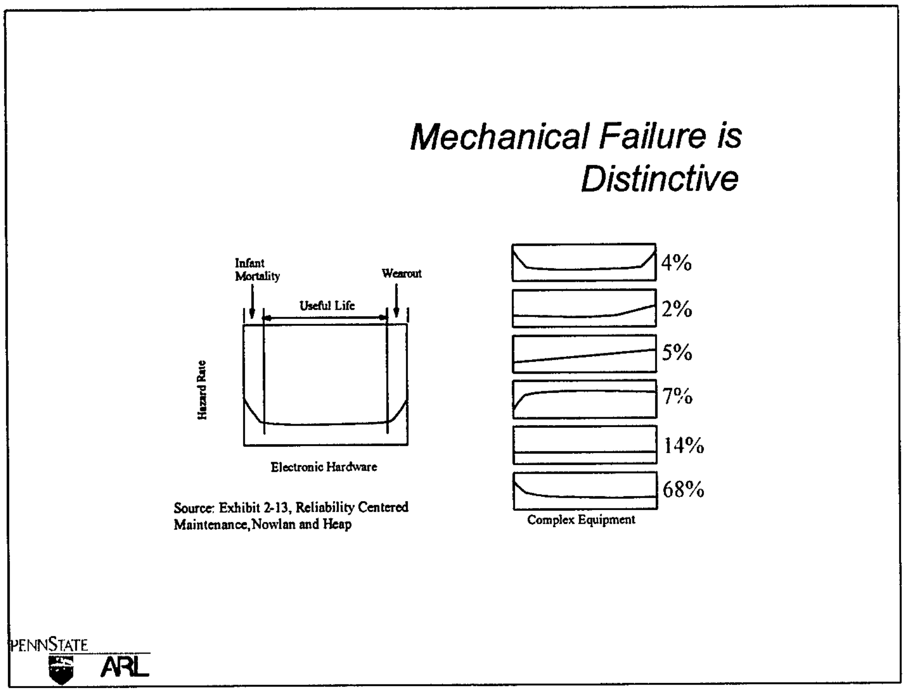
Predicting the future must rely on a probabilistic prediction based on a population of like machines when the time the predicted event (end of useful life) is long. The objective is to move to an increasingly deterministic prediction of remaining useful life based on monitoring of the individual piece of equipment and on developed models of the evolution of faults in the machine.

The user must place his confidence in one or the other of the prediction approaches. In a time-directed maintenance situation he is "by definition" depending on the probabilistic prediction based on a population of like machines. That is, because most (nearly all) of the machines in the population last for x-hundred hours and this machine has y-hundred hours (less than x), it is safe to undertake this next mission prior to a maintenance action.

There comes a point in the evolution to end of useful life where properly constructed deterministic predictions based on monitoring of the individual machine and models of failure evolution reach a threshold of confidence where it is more prudent to trust that prediction over the probabilistic prediction.

Diagnostics and prognostics research must reach that level of confidence before the remaining useful life of the equipment is less than the "critical prediction horizon" or the time that the model requires to refine its prediction and the time that the owner needs to affect the required maintenance action.

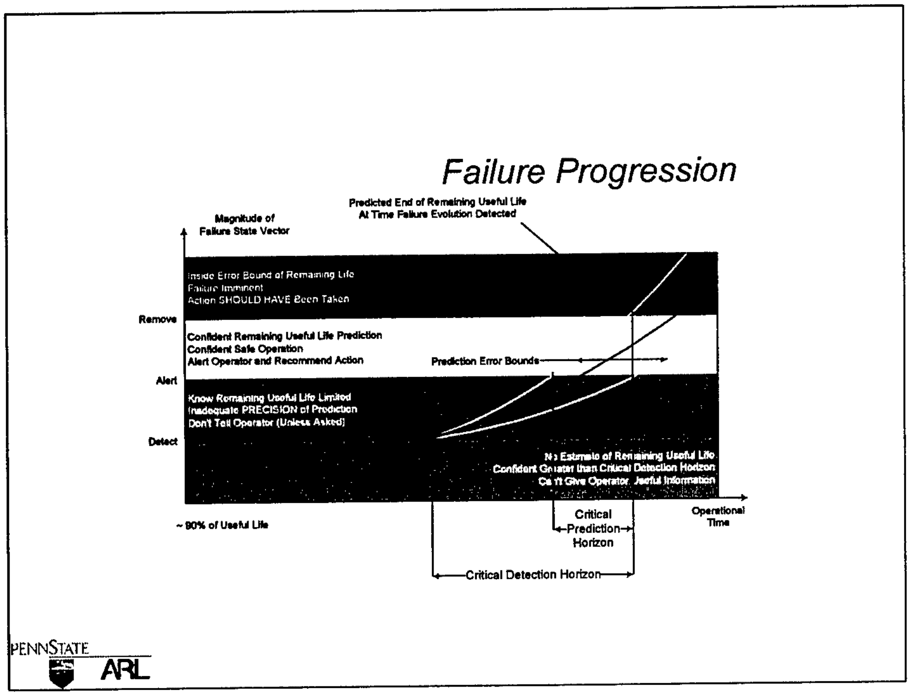


As a part of reliability-centered maintenance development, Nolan and Heap studied actual aircraft equipment to determine the observed hazard rate (probability of failure) as a function of operating time. Traditional reliability analysis depends on the concept of a "wearout" period as shown in the typical "bathtub curve" for electronic equipment. Unfortunately, mechanical equipment was not observed to behave so nicely.

Of the complex mechanical equipment items studied, only 11% exhibited a hazard rate curve in which a rational argument could be made for a time directed maintenance task. That is the time at which the hazard rate exceeds an acceptable limit. Those curves are the top three on the right.

The other 89% of the equipment exhibited a random failure (constant hazard rate) pattern at the time of maintenance or repair. For those equipment, there is no statistical basis for conducting maintenance at the applied periodic interval.

The bottom curve on the right shows the left side of the typical "bathtub curve". This may in fact be a true bathtub curve where the useful life of the equipment was truncated before reaching the wearout phase. The problem is that there is no way to know whether wearout would have started to occur (statistically) shortly after the maintenance action (in which case maintenance was conducted at the proper time) or if the wearout occurred much later (in which case useful machine life was discarded).



This generalized curve of machinery failure progression shows the evolution from the point where a "terminal" failure initiates (probably at the microscopic level at approximately 90% of life) to the end of useful life and beyond. The four zones represent increasingly accurate and precise predictions of remaining useful life.

In the first zone, the only tool available to predict remaining useful life is probabilistic based on a population of like machines. This encompasses most of the life of the equipment. Sometime after the fault initiates, it becomes observable using whatever surveillance methods are applied. At this point, the system "knows" that a fault is determining the remaining useful life and the probabilistic prediction based on a population of like machines is superceded by an analytical prediction. It will take some number of iterations of the analytical prediction process to refine the prediction and increase its certainty to a level appropriate to alert the operator. This occurs while the fault evolves through the second zone.

At the time that the confidence in the predicted remaining useful life reaches a level acceptable to the operator AND the remaining useful life reaches the "critical" prediction horizon", the operator is alerted. He then has the amount of operating time he specified to conduct the indicated maintenance action before the equipment progresses to the "remove" level of severity. Once the severity of the fault reaches the "remove" level threshold, failure can occur at any time.

Moubray's P-F Curve

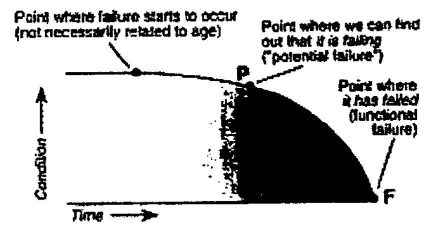


Figure 5.6: The P-F curve

The P-F interval is the interval between the occurrence of a potential failure and its decay into a functional failure.

Moubray, John, *Reliability-centered Mainteance*, Industrial Press, Inc., 1992

PENNSTATE ARL

A generalized machinery failure evolution curve is presented in the RCM literature, this taken from Moubray.

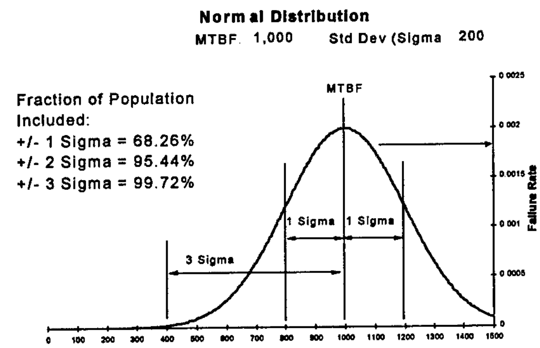
The vertical axis on this curve represents "health" and is the inverse of the vertical axis on the Penn State failure evolution curve which represents damage.

Important points to note on this curve are that the point at which failure starts to occur may or may not be related to age. There is a point where the fault is detectable and there is a point at which the equipment has reached "functional failure". In the RCM vernacular, functional failure is analogous to our "end of useful life"

A significant difference between this curve and the curve presented by Penn State is the lack of the intermediate alert point. Depending on one's point of view, the alert point from Penn State's curve falls either on point "P" or between point "P" and "F".

I contend that establishing a separate threshold after detection, but before functional failure, is an important addition to the RCM perspective. This point is intended to account for the fact that an operator will have a number of equipments, all of which are at some point in their evolution to failure and triage is imperative. Providing information prior to the time at which it is necessary for him to act interferes with his ability to operate the fleet or enterprise.

A Simple Failure Distribution



PENNSTATE ARL

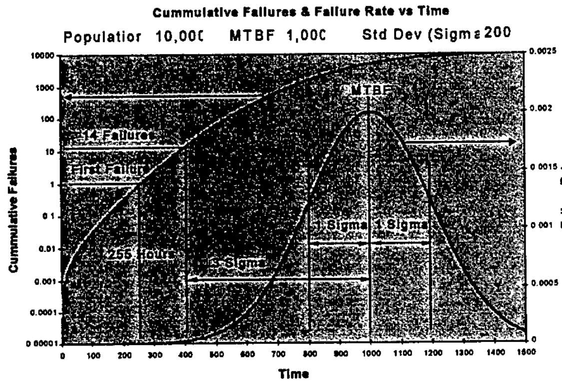
A little description of statistics and what they mean in a planned, time-directed maintenance philosophy.

The simple failure distribution shown above is the normal distribution. It is chosen because it is the easiest to work with and most familiar to most readers, but also because it fairly represents a wearout failure process for a population of equipment.

Above is shown the normal distribution assumed based on an analysis of a large population of machines over a period of time. It is not meant to be a projection of life, but rather a representation of experience in the population. The mean of the population is observed to be 1,000 with a standard deviation of 200. The mathematics of the normal distribution the define that the percentages of the populations shown will be contained within the lifetime of + or - 1,2, or 3 standard deviations or sigma.

As you can see, the failures that occur prior to three standard deviations (3-sigma) before the mean will be 0.14% (1/2 of those not contained within +/- 3 sigma. That seems like a very small number and might represent a good place to establish a maintenance level for this equipment item.

Effect of Time-Based Maintenance



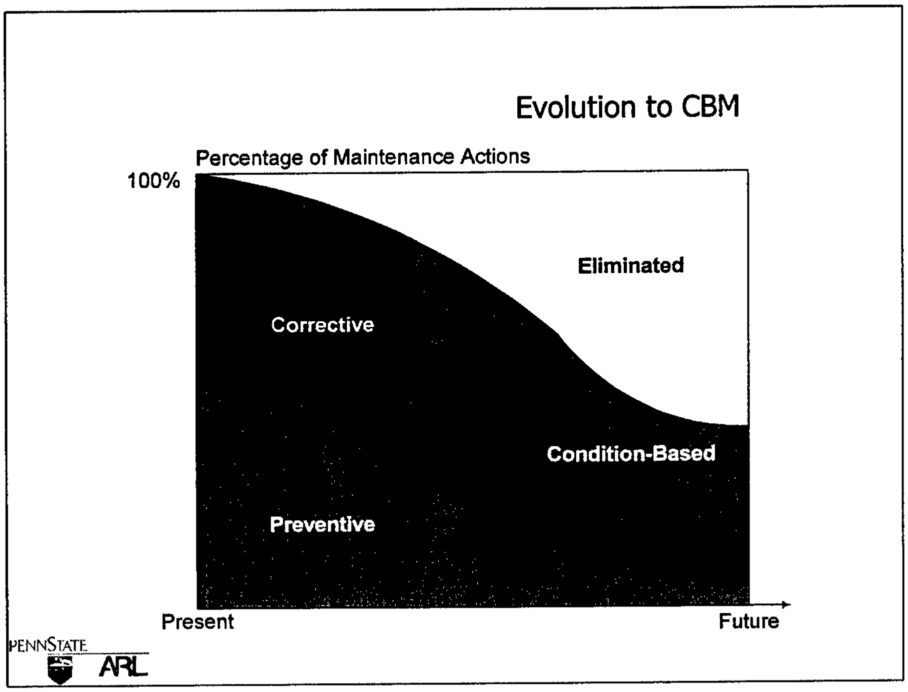
PENNSTATE ARL

Above is the normal distribution presented elsewhere with cumulative failures plotted for a population of 10,000 items. While this may be a large number for the types of equipment usually considered, it is chosen to make the numbers work in integers rather than fractions. The impact on the enterprise is the same whether we talk about a population of 100, 1,000, or 10,000.

As can be seen, the first failure in this population of 10,000 will occur statistically after only 255 hours of operation. The problem is that the statistical prediction will tell you absolutely nothing about which of the 10,000 units that will be.

If this were a critical item, the maintenance interval might be set a 3-sigma below the mean. Setting the maintenance interval at that point implies that the owner is willing to accept 14 failures in the population of 10,000 and that he is willing to "throw-away" useful life (in 5,000, those that lie on the right side of the mean, more than 600 hours) on 9, 986 of the items.

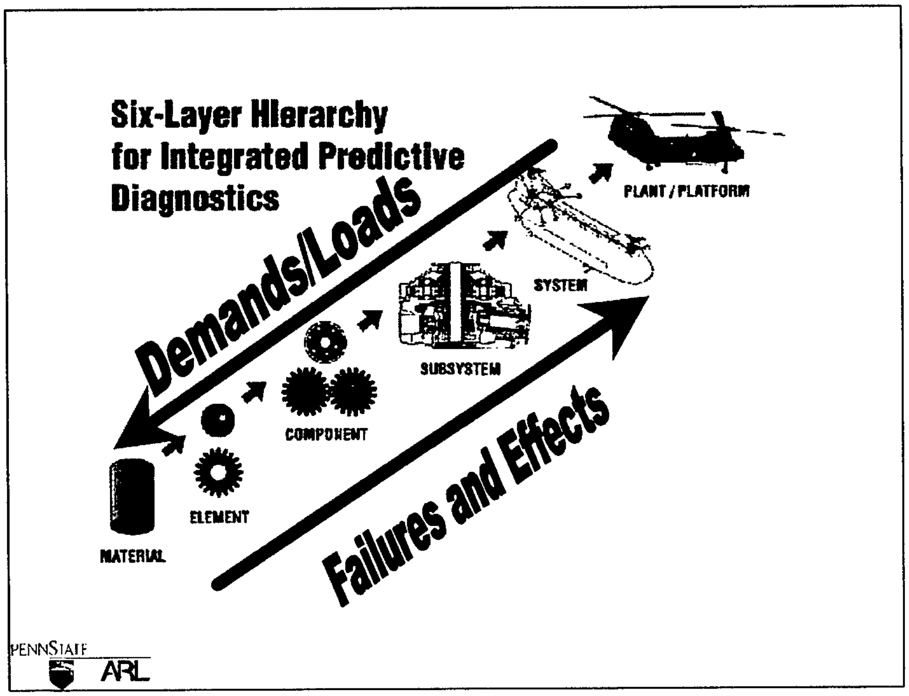
This may be an acceptable trade-off in some applications, but it highlights a great opportunity for monitoring on an individual equipment basis and analysis of the health of the equipment if it can be performed cost effectively and reliably.



The evolution to a more efficient and effective maintenance philosophy will occur over time and will always consist of some mix of condition-directed, corrective, and time directed maintenance actions.

The current state in the military is that we perform a large amount of preventive maintenance, a large amount of corrective maintenance, and some condition-directed maintenance. The objective is to eliminate unnecessary maintenance actions, conduct most maintenance on-condition when the particular unit requires it, conduct some corrective maintenance because the monitoring systems will never be perfect and it will always make sense to operate some equipment in a "run-to-failure" mode (e.g., room lighting), and maintain some equipment solely on time.

Those items which would remain in a time-directed maintenance mode would be those with moderate level of consequences of failure (too much to allow to run-to-fail) and a very tight failure distribution around a mean. For example, if you consider a normal distribution with a mean of 1,000 and a standard deviation of 10, this might make a good candidate for time directed maintenance. If the population exhibited a mean of 1,000 and a standard deviation of 300, it probably would not be a candidate for time-directed maintenance actions.

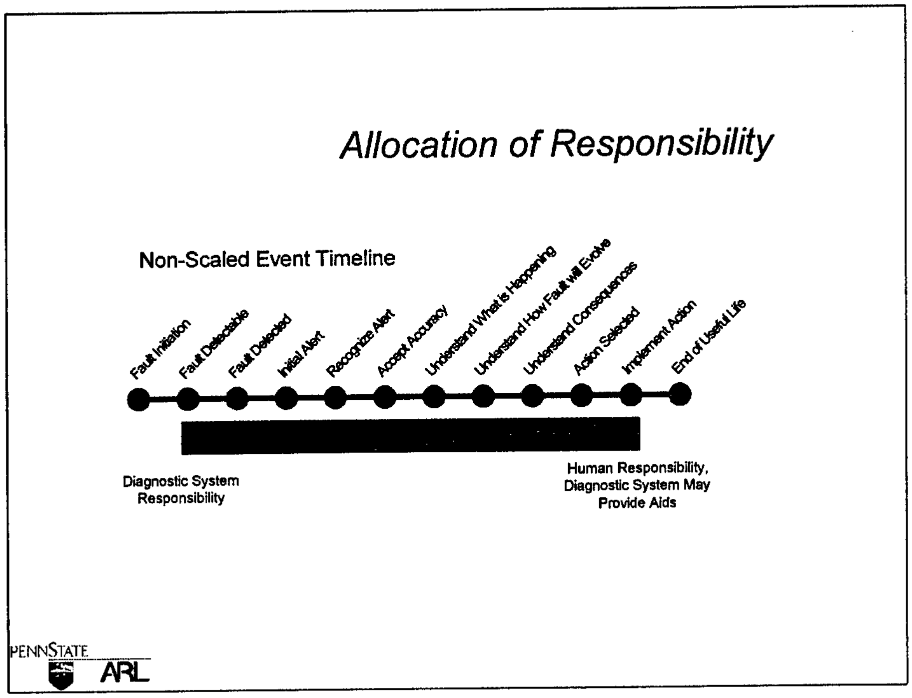


In order to organize our research in a manner that allows results to be applied to a variety of equipment, we needed to establish a hierarchy of a plant or platform. This enables us to understand failure and the observables of failure in materials and to translate them into a variety of applications. The generalization comes from the fact that mechanical systems and subsystems comprise standard components including gear meshes and bearings. If we can monitor and understand failure progression as a function of load in these components, we can translate that up to the plant or platform level.

The basis of this approach is that all demands and loads on the system come from the plant or platform which is the point at which an asset is assigned a definable mission, e.g., carry troops across the beach. This mission is the driving factor and all elements of the plant or platform are consumables that must be managed in accomplishing the mission.

Failure does not start until the ability of the material to carry the load demanded of it from the plant or platform exceeds its strength. Certainly environmental factors impact the strength of the material, but failure does not occur until the load imposed exceeds the environmentally reduced strength of the material.

Effects of these material failures progress back up the hierarchy to effect the mission of the plant or platform. It is not until the mission is effected that the operator should be concerned other that managing consumption of the equipment.



Since we are attempting to automate or at least support the human decision process in operational equipment, it is important to consider where the computer's responsibility ends and the human takes over responsibility.

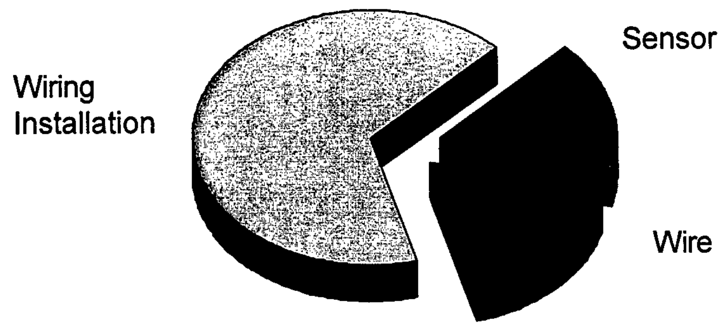
The above represents a continuum in the decision process that must be traversed prior to an action being taken. Each of the steps are accomplished in series from left to right. In experts, they may appear to be accomplished in one leap, but that is because training and experience have "hard-wired" the response based on inputs. In development of the training process, then, each of these steps must have been considered.

Each application will be amenable to allocating greater or lesser responsibility to the computer. Previously, humans have been very reluctant to give up authority to the computer in any but those cases where the time-frame of response was too fast for the human to manage, e.g., fighter aircraft flight controls.

In the current fiscal constrained environment, however, greater emphasis is placed on designing the human out of the loop and enabling more autonomous action by the system.

Wherever a particular application lies on this continuum of responsibility, it is imperative that the systems and technologies developed accommodate human intervention wherever the owner desires.

System Costs



Typical Industrial Instrumentation Costs

PENNSTATE ARL

In determining how we should approach implementation of advanced monitoring technologies for diagnostics and prognostics, we investigated where the costs go in installing on-line monitoring systems. We found that typically 60% of the cost is installation of wiring.

Further, the most vulnerable and unreliable portion of the system is the wiring. It is prone to be cut or break along its length and problems with connectors are the bane of any monitoring system.

We have chosen to attack this problem by developing a wireless approach to information collection. This entails a hierarchical design where monitoring and analysis are conducted at low levels in the mechanical system hierarchy presented elsewhere. Pushing the processing out to the component level has two positive effects.

First, it allows generic developments that can apply to a large variety of applications. It is inherently object-oriented and associates processing with a tractable portion of the system, i.e., predicting the life of a bearing is easier than predicting the life of a transmission made up of multiple bearings and gears.

Second, it dramatically reduces the transmission bandwidth required for communication. This distributed processing reduces the data flow from an accelerometer measuring 20 kHz vibration at 24 bits resolution for a total bandwidth of 480,000 bits per second data stream to an information stream of a few bytes on demand or periodically stating the current health of the monitored bearing.

Why Wireless?

- Typical Helicopter HUMS Installation: 35 to 40 Sensors
- Projected Cost Reduction using Wireless

– Sensors	$0	Sensors Same Cost
– Sensor Installation	$0	Equivalent Installation
– Wiring Installation	$70,000	35 Sensors @ $2,000
– Wiring Cost	$17,500	35 Sensors @ $500

- Savings/Aircraft $87,500

MAWCAD, PAX, Phase II SBIR, Invocon, Inc.
Topic: Wireless Airborne Instrumentation System
Reduce Wiring Time for High Performance Aircraft Flight Testing from 9 Months to 1 Month
Scheduled Complete Early CY 98

PENNSTATE ARL

Wires are the most expensive, least reliable, and most vulnerable portion of the monitoring system. This provides an example of potential economic benefit of applying wireless sensing in an airborne application - helicopter health and usage monitoring systems.

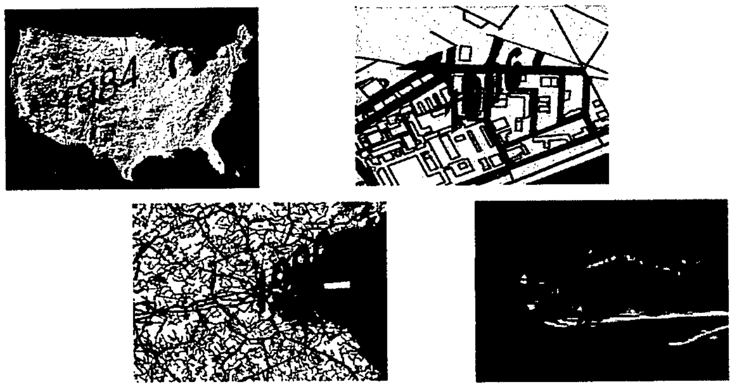
The analysis presumes a typical HUMS installation will comprise around 35 or 40 sensors. Breaking the installed cost of the sensors and wiring into four categories the savings a wireless installation offers over a conventional wired installation is shown.

Sensors and sensor installation are shown at the same cost for either option. This is a design goal to make our wireless sensors form and fit compatible and cost competitive with conventional wired machinery monitoring accelerometers.

Sensor wiring installation is the largest saving. At a conservative cost estimate of $2,000 labor (fully burdened, including QA, etc.) per channel and assuming 35 sensors per aircraft, savings of $70,000 per shipset are projected. Additional savings of $500 per channel for sensor wiring translate to $17,500 per shipset for a total of $87,500 or approximately 1/3 the total installed cost of the system.

Technology to enable wireless transmission of data in an aircraft environment is being adapted from an SBIR for high-performance aircraft flight testing wireless data acquisition by Invocon, Inc. The technology is a dynamically reconfigurable wireless array of sensors.

10,000 Network Connections



Source: MIT Media Lab
http://www.media.mit.edu/pia/Pubs/TTT_9610

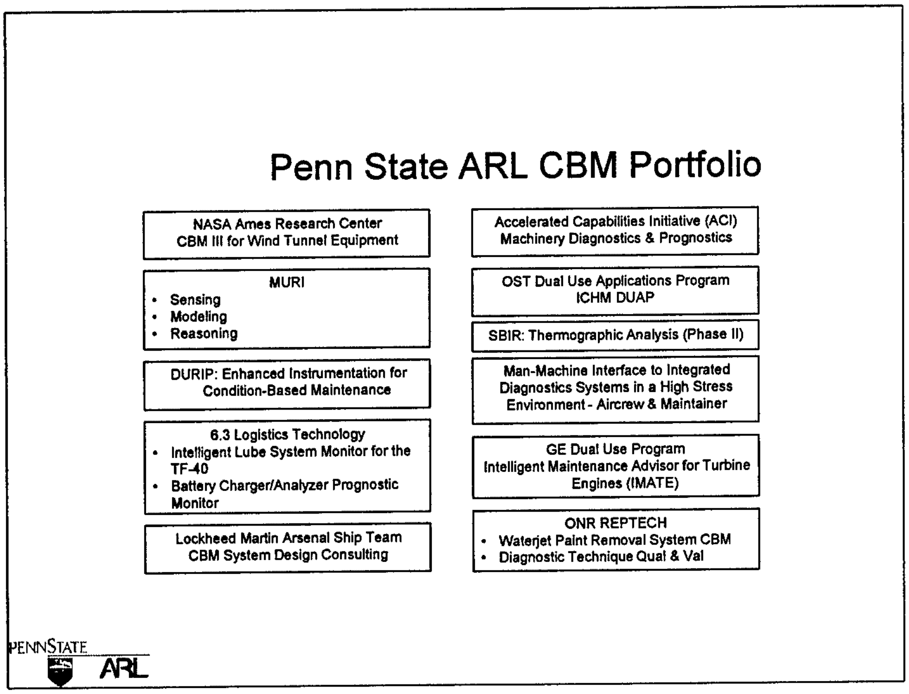
PENNSTATE ARL

There are a number of technologies advancing at an unprecedented rate, one of them being the internet.

Above shows the growth of internet connections in the US over an 18 year period.

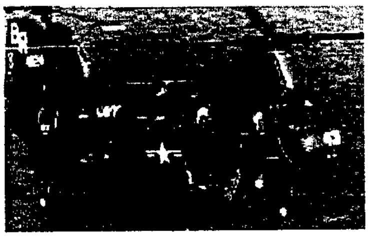
In 1984 there were 10,000 network connections in the continental United States. Six years later, that same number of connections were established in the Boston Metropolitan area. Six years later the MIT campus had 10,000 network connections and in 2002, one building, the Media Lab building, is expected to have 10,000 connections.

While the availability of network connections is important, it is less that than the industry and technology base that has grown to support this explosion. We should be directing our efforts toward approaches consistent wherever possible with the internet. Using internet protocols, using software developed for the internet, and applying standards as they evolve. A commercial internet capable of supporting e-mail and web-browsing will not by itself solve our problems, but the tools that evolve to support the internet should certainly help us.



Penn State ARL has assembled a broad portfolio of projects in Condition-Based Maintenance. The projects range from basic research in the MURI to very applied, particularly in the work on NASA wind-tunnel support equipment. Other projects span the range from research to application according to the particular sponsor and application requirements.

REPTECH Diagnostic Technique Qualification & Validation



OBJECTIVE

Develop and validate a procedure that will qualify diagnostic techniques for mechanical equipment to avoid potential for excessive false alarms as HUMS enter fleet.

SOLUTION

- Collect believed good data on a full squadron of H-46 aircraft (10 aircraft)
- Archive data, make available via Intranet for rapid analysis
- Conduct Measures of Effectiveness/Measures of Performance on all Analyses Conducted

BENEFITS

- Reduced false alarm rate at implementation of Health and Usage Monitoring Systems (HUMS)
- Dress rehearsal of squadron level response to HUMS alerts

RELATED EFFORTS

- ONR Condition-Based Maintenance Advanced Capabilities Initiative: Development of advanced diagnostic technologies
- Integrated Mechanical Diagnostics Implementation roadmap
- Advanced Maintenance Environment (AME)

IMPLEMENTATION

- Develop and demonstrate means and metrics to independently qualify alternative diagnostic technologies
- Transfer capability to program offices and depots for use in acquisition selection

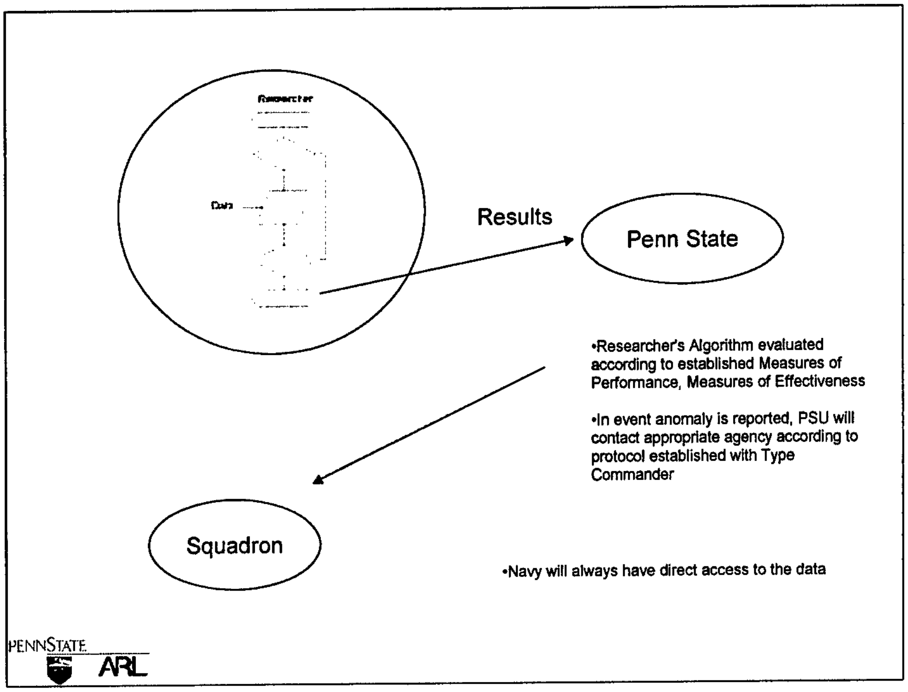
PENNSTATE ARL

One of the key limiting factors in development of reliable diagnostic and prognostic technologies is lack of high-fidelity data correlated with actual fault conditions in equipment. A limiting factor in application is a lack of reliable measures of performance and effectiveness for the techniques. This project begins to address both concerns.

The intent is to collect a large database of high-fidelity vibration data on a fleet of active aircraft. This data will be directly correlated with previous seeded fault test-stand data collected by the US Navy. The datasets collected will be made available in near-real-time via an intranet to a variety of researchers each of whom will analyze the data and report results to the Penn State repository.

Additionally, the monitored components of the aircraft (aft main transmission) will be tracked to the repair facility. When a transmission that is in the monitoring program is removed from service for either cause or time, its condition will be assessed at the depot. These "ground truth" results will also become part of the repository at Penn State.

These results will be compared against a set of measures of effectiveness and measures of performance that are currently under development in another project. This will enable the evolution of an unbiased measure of how well a particular application as well as a measure of the cost of implementing the technique in terms of sensor fidelity, processing requirements, monitoring time, etc.

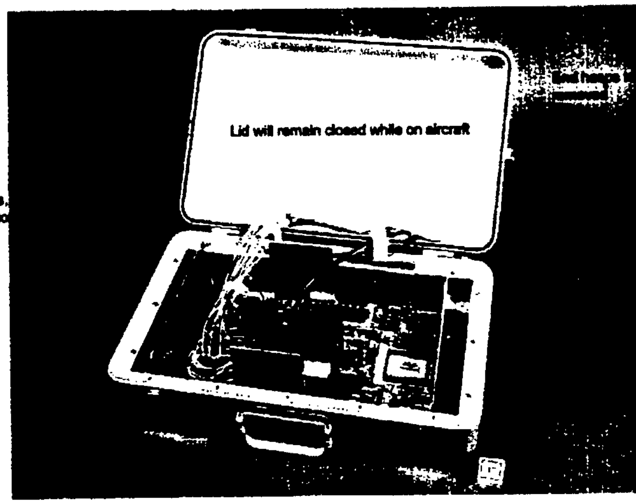


This project entails a high degree of interaction between researchers, Penn State ARL, and the squadron. Researchers have agreed to analyze data from individual flights within seven days of receiving notification of its availability. The results of these analyses must then be reported to Penn State ARL along with performance metrics relating to computing load and data quality required. These results and metrics will be compared among researchers by data set and over all data sets.

In the event an anomaly is discovered by any of the researchers, Penn State will contact the Type Commander in accordance with an established protocol to determine the response at the squadron level. These analyses are treated as additional information, all maintenance decisions in the squadron remain based on OPNAVINST 4790 and the Naval Aviation Maintenance Plan.

Owing to the Navy's investment in the data and infrastructure, access to both data and the results of the analysis by individual researchers will be assured for the Navy. Limitations on distribution of data and/or results of analyses will be determined as part of the agreement providing access to the data.

Information Logger in Chassis

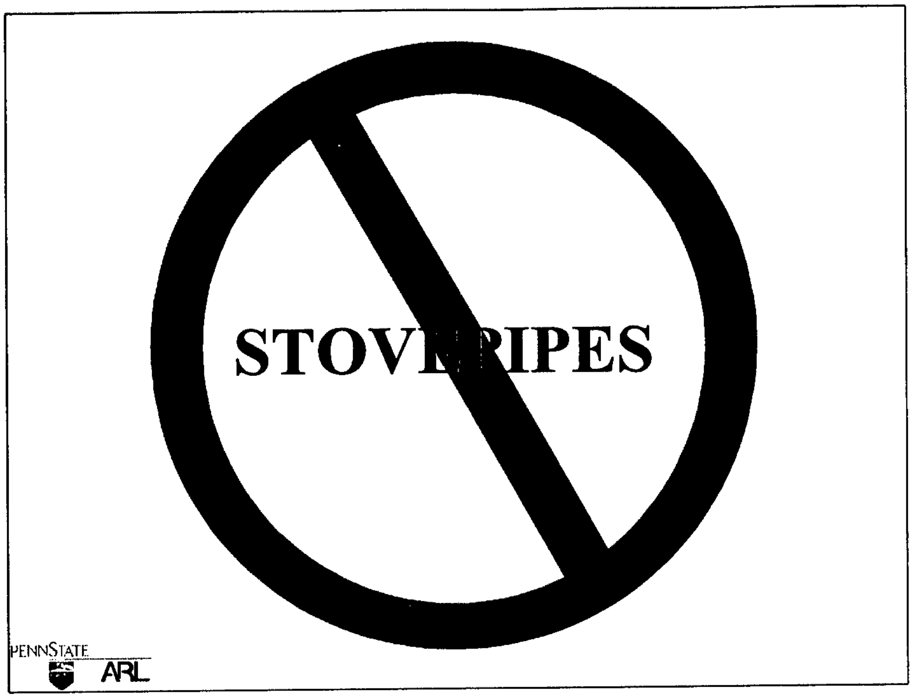


Key to building a successful and useful data archive is populating it with archival quality data. Bandwidth, dynamic range, and all signal conditioning/pre-processing done to the data must be clearly documented and sufficient for most of the research community.

Key to being able to collect data in an operational fleet environment without on-site technical personnel is a device and process that minimally interferes with the performance of the mission and does not place an undue burden on the squadron. The information logger shown is designed with both of these requirements in mind.

The technical specifications on the recorded signatures were reviewed by several members of the diagnostic development community. While each reviewer had specific requirements, some of which were conflicting, the box was designed to be a reasonable compromise that could collect the best possible data within the operational constraints of fleet operations. The box stores all information digitally and is designed for post-flight download directly to a web-server for dissemination. Detailed technical specifications provided elsewhere.

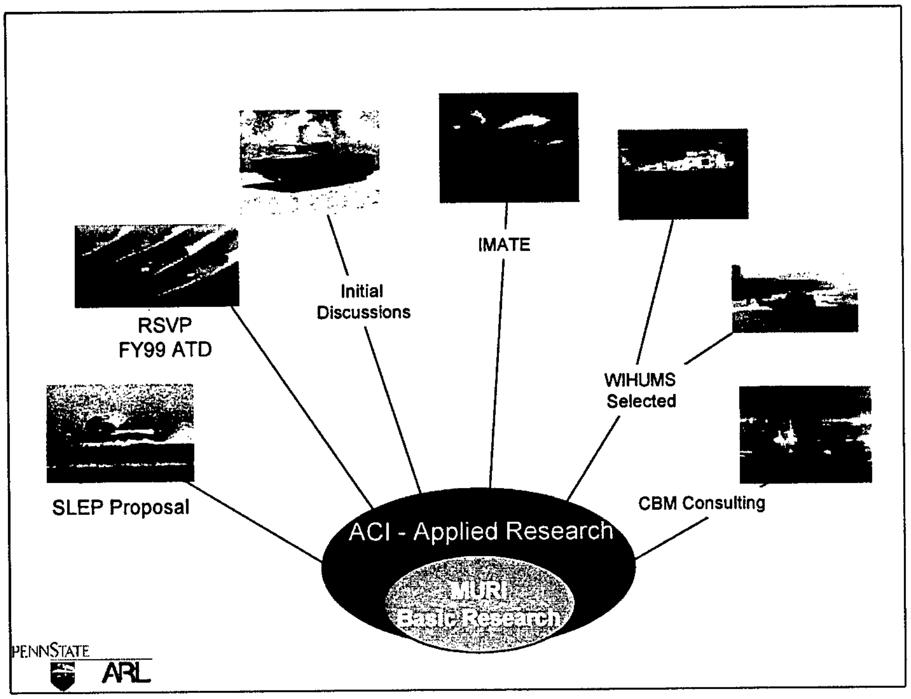
The information logger must also meet flight safety requirements and be operable by the crew-chief without an undue burden. The box was designed for and met flight clearance requirements with interim clearance granted 3 Oct 97. From an operational standpoint, the crew straps the logger into the aircraft, connects 1 plug to power and a second to data, flips one switch, and goes flying.



A fundamental precept of our approach to this technology is that single-point solutions are unacceptable. Every design and development must be developed with a broad range of applications in mind. While this may require some performance or cost compromises in some applications in the near term, the ability to use the technology across a broad range of applications results in a market volume that enables order-of-magnitude cost reductions. If the technology is redeveloped for every application separately, non-recurring engineering costs as well as costs of building installed hardware will be too large to justify the investment.

A specific and apropos example is the need for commonality between commercial and military instantiations of the equipment. Our approach favors distributed, highly-autonomous, devices monitoring and determining the health of the components. This requires that there be many of these devices per platform. In order to be affordable, they must be made in large quantity. In order to reach large production quantities (millions per year) they must be common in large part across a multitude of applications. Thus a bearing monitor in a paper mill should vary minimally from a bearing monitor on a helicopter tailrotor driveshaft.

The phrase I like to use is “commercially viable meeting military requirements.” This is achievable if the military uses its leverage in the research budgets to develop technologies that can meet this objective.



We are working very hard to ensure that the results of our research do not die in the laboratory. All acquisition and development programs for the foreseeable future will be striving to realize the benefits of condition-based maintenance as we describe it.

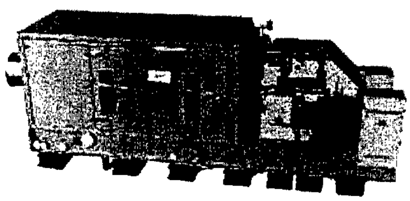
On the military side, we are trying to coordinate our developments to fill needs with major acquisition programs. As shown above, we have been successful in becoming directly involved in many. These efforts will continue.

The issue in transitioning technology is timing the research program such that it reduces risk to the appropriate level for the acquisition program manager to be able to assume the risk in a program. It is inappropriate to expect the program manager to assume technical, program, schedule, or cost risk to incorporate unproven technology. The problem is that it is difficult to carry a development program far enough along to reduce the risk to that level without the direct support of the program manager.

The research community is frequently asked the question "What have you done for us lately?" The answer is ALL the new technology that is being applied in this acquisition. The problem is that the time between technology maturation and insertion is so long that the tie back to the original research and development effort is often lost.

Integrated product teams and similar initiatives are attempts to shorten the time and improve linkage between development and application.

Demonstration Target



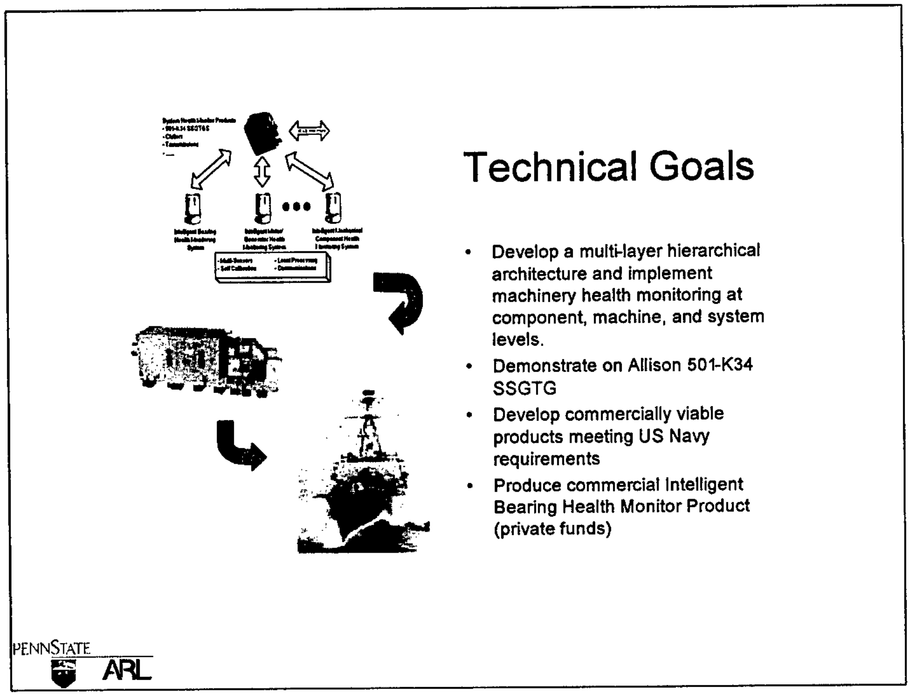
Allison 501-K34
Ship Service Gas Turbine Generator

PENNSTATE ARL

In the Office of Naval Research Future Naval Capabilities Option (FNCO) program we were fortunate to receive an award in the mechanical diagnostics and prognostics program. The demonstration vehicle for the technology developed was chosen by the proposing team as the Allison 501-K34 (AGT-9140) Ship Service Gas Turbine Generator Set in the DDG-51 class. Generally, the scope of the project is the equipment contained on the skid shown.

The Allison GenSet was chosen after Allison Engine Company was selected as a team member. Involvement of the original equipment manufacturer (OEM) is considered by us to be critical to the success and ultimate transition of this technology. Rather than pick the application and try to recruit the OEM, we began a dialogue with Allison and selected the 501-K34 as the item of their equipment providing the best demonstration vehicle for our technology considering the scope of the effort, available data and test resources, and the guidelines of the opportunity.

It is important to note that it is not the intention of this project to develop a complete health monitoring system for the 501-K34. Rather, we are using the 501-K34 as the equipment on which we demonstrate technology being developed for a wide variety of applications. Thus we may develop and implement some technologies not totally driven by the requirements of the genset and we may not undertake other challenges that might be of interest to the application but are outside the scope of this project.



Our proposal outlined the goals of our project as above. The first is the primary goal of our effort.

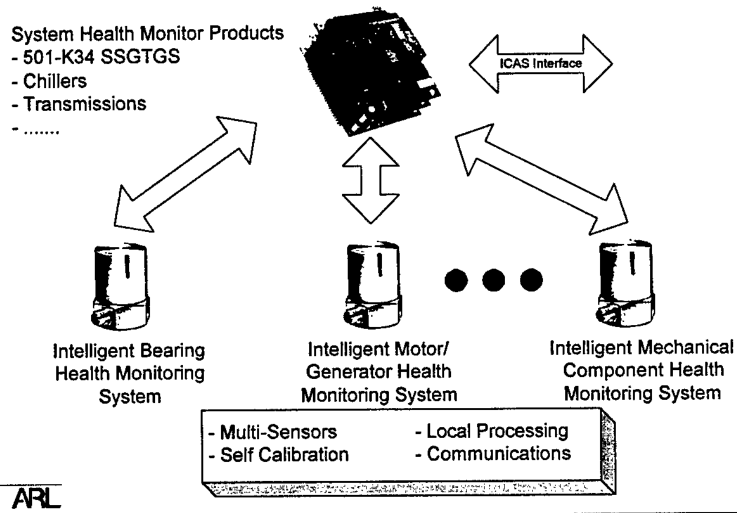
We intend to develop and demonstrate an architecture, hardware, and software that enables cost effective machinery health monitoring and ultimately prognostics by distributing processing to the component, machine, and system levels. The details of the logic of this approach are described elsewhere but it entails using mainstream technologies where possible (like PC-104 and Compact PCI) to leverage production and development tools.

The demonstration vehicle for our technologywil be the Allison 501-K34 SSGTG(AGT-9140) working in cooperation with the OEM, Allison Engine Company.

A key driver for our development is commercially viable products that meet US Navy needs. This provides great leverage on the USN research funding to place items "on the shelf" for later removal as "COTS" that fit precise navy requirements.

The first such item planned is an Intelligent Bearing Health Monitor that will be commercialized by Oceana Sensor Technologies, Inc. We are confident that a near-term product will be a viable commercial product without reaching all of our cost, size, and weight objectives which become more important on high performance military platforms.

System Level Architecture



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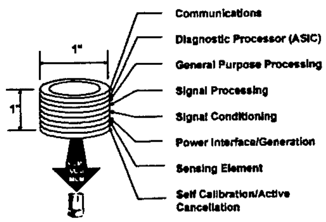
Product Description

Intelligent Component Health Monitor



- Integrated multi-parameter sensing and processing - produces component health assessment vice data
- Reliable wireless communications
- Accommodate self calibration and active noise canceling
- Define and consolidate functions to produce ASIC for large quantity production

PENNSTATE ARL

PENNSTATE

Applied Research Laboratory

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State College, PA 16804-0030

25 February 1998

SUBJ: Workshop on Maintenance and Diagnostic Requirements for the AGT-9140 Gas Turbine Generator Set

Dear Recipients,

Attached is the information package on the subject workshop conducted in September 1997. The package contains the following documents:

1. Minutes and specific results of the meeting.
2. Penn State-ARL presentation of a vision for full shipboard implementation of machinery diagnostics and condition-based maintenance.
3. Penn State-ARL presentation on condition-based maintenance and the ONR-funded Future Naval Capabilities Option program.
4. Penn State-ARL presentation on conduct of the workshop and reliability-centered maintenance.
5. Attendees' comments on the workshop.

Information is provided for your use. Additional copies are available upon request. Any comments on content would also be appreciated and should be directed to the undersigned.

We would like to thank the participants in the meeting for their contribution to our efforts. We believe that important information was collected efficiently and viewpoints of all stakeholders in the process were represented. This step is an important event in development of next generation systems and technologies for condition-based maintenance of mechanical systems.

Regards,

G. WilliamNickerson
Head, Condition-Based Maintenance Department

GWN/smg

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Table 4 – Ancillary System Results...11

Appendix A – Penn State – ARL Presentation "Blue-Sky and Green November"

Appendix B – Penn State – ARL Presentation "Condition-Based Maintenance"

Appendix C – Penn State – ARL Presentation "Reliability-Centered Maintenance Analysis"

Appendix D – Parting Comments for the Good of the Order"

501-K34 Maintenance and Diagnostic Requirements WORKSHOP Meeting Minutes

Executive Summary

This document describes the results of a workshop to identify maintenance and diagnostic opportunities in the Allison 501-K34 Ships Service Gas Turbine Generator (AGT-9140). This workshop was targeted at determining the location, type, and hierarchical structure of health monitoring technology being developed under a Future Naval Capabilities Option (FNCO) for Machinery Diagnostics and Prognostics under sponsorship of the Office of Naval Research.

The approach of the workshop was consistent with, but not a direct application of, the Reliability-Centered Maintenance (RCM) process. RCM was developed for the purpose of defining a preventive maintenance philosophy. Our intent is to investigate the application of condition-based maintenance (CBM) to a complex mechanical system. While many of the concepts and tools of RCM apply and should be used, the "weighting factors" at decision points and some of the considerations should be different. Certainly the technology available for monitoring and diagnostics of mechanical systems is dramatically different than that available when RCM was developed. One of our intents was to evaluate an alternative, "CBM-centric" application of RCM principles in an effort to establish new tools and techniques for an updated look at the process of establishing "applicable and effective" maintenance practices in the context of available and developmental diagnostic technology.

The workshop brought together experts from all aspects of the life cycle of the application equipment, AGT-9140. The attendees included the Original Equipment Manufacturer, In-Service Engineering Agent, Life-Cycle Manager, Direct Fleet Support Activities, and end users from the USS THE SULLIVANS. The combined experience of these experts interacting with the technology developers provided an interesting discussion of the real problems experienced with the AGT-9140 during its life cycle and allows the development community to address specific issues.

The attendees are listed with contact information in Table 1, the meeting is summarized, and presentations made by the FNCO team are included as appendices. Experienced problems, rationale for attention to them and potential approaches discussed during the workshop are listed according to subsystem in Table 2, Table 3, and Table 4. The FNCO developers are using this information to refine specific technology developments for the current project.

501-K34 Maintenance and Diagnostic Requirements WORKSHOP Meeting Minutes

Introduction and Background

This workshop is an important step in the definition of specific technologies to be developed in the FNCO program led by Penn State ARL. This project is described in a briefing included as Appendix B to this document.
We attempted to bring together all stakeholders affected by the results of our work. Of course, this is impossible, but the attendees do represent the majority of organizations involved in maintenance and operation of the AGT-9140 system. Any organization that might not have been represented is strictly due to oversight or a limitation owing to logistics of the meeting. No intent to exclude any valid viewpoint is intended or desired.
A workbook was provided to all attendees to assist in preparation and for use during the workshop. Copies of this workbook are not appended to this document, but are available upon request to Penn State ARL, contact Mr. Bill Nickerson (see attendee list in Table 1).
Attendees reviewed the materials prior to the workshop and were familiar with the objectives and the methods applied during the workshop. The approach was a team effort with open discussions and the final results determined by consensus.
The efforts of all attendees were vital to the success of this task. By selecting experienced individuals from the 501-K34 end-user (Navy); the equipment manufacturer (Allison Engine Company); and research community (Penn State University), we developed what we believe to be an accurate picture of the experience with the AGT 9140 in service. This will enable selection of technologies for demonstration that will show the benefits of Condition-Based Maintenance and the performance of the diagnostic technologies developed during the project.

501-K34 Maintenance and Diagnostic Requirements WORKSHOP
Meeting Minutes

Summary

The meeting was held at IDAX Corporation in Norfolk VA on September 25-26, 1997. The meeting started on September 25 at 8:30 am. Bill Nickerson (ARL Penn State) gave an overview of a Condition-Based Maintenance Scenario entitled "The Blue-Sky, Green-November" presentation, included as Appendix A. The presentation illustrates the vision of a ship of the future applying the capabilities of a network of sensors and communications systems to perform maintenance, diagnostics and prognostics of the ship important subsystems. An important linkage is a direct and automated tie to the logistics support system to deliver necessary parts and materials in a timely manner without extensive human interaction.

Bill then presented and overview of condition-based maintenance (CBM) and the Accelerated Capabilities Initiative (ACI) in Machinery Diagnostics and Prognostics (now called the Future Naval Capabilities Option, FNCO, Program). This review details the efforts underway at Penn State with a consortium of companies and NSWCCD, to develop a multi-layer hierarchical architecture and implement machinery health monitoring at component, machine, and system levels. The demonstration vehicle for this project is the Allison 501-K34 SSGTG (AGT-9140). A key development of the FNCO is an intelligent component health monitor (ICHM) sensor to detect and diagnose machinery component health. The ICHM will be networked to a system health monitor (SHM) to obtain system-level health information. At the highest level, the platform level monitor will interface to the platform level monitor, presently Navy- ICAS. This presentation is included as Appendix B.

Les Johnson followed with a presentation on reliability-centered maintenance (RCM) analysis. RCM was developed in the DOD and civil aerospace industries to addresses reliability of aging components. The result of these earlier studies was the recognition that traditional scheduled preventative maintenance did not guarantee improved reliability, in fact, the reliability was worse in some cases due to misassembly during maintenance or scheduled overhaul. Hence, the goal of reliability-centered maintenance was to identify failure effects and criticality analysis in an effort to minimize unnecessary maintenance procedures and to identify possible areas, which need design improvement. Les explained that the goal of the workshop is to identify and document areas of the 501-K34 SSGTG, which can benefit from the application of ICHM sensors. Les presented an overview of the failure modes and effects analysis (FMEA) and a worksheet to identify potential ICHM sensor applications. This presentation is included as Appendix C.

Participants were separated into three groups: 1) engine, reduction gearbox, and accessory drive; 2) generator and electrical control systems; and 3) ancillary systems. Each group was responsible for different subsystems of the 501-K34. Membership in groups was based on individual background, experience, interest and balancing number of personnel in each group. Group leaders were selected for each of the groups. Greg Colman (Allison) was selected leader of the first group. The first group had responsibility for the engine; reduction gearbox and accessory drive systems. Dr. Jeff

501-K34 Maintenance and Diagnostic Requirements WORKSHOP Meeting Minutes

Kohler (Penn State) was selected leader of the Generator and Electrical Control Systems Group. Chris Armitage (AMS) was selected leader of the Ancillary Systems Group. This group considered the lube oil system, fuel system, bleed air system and pneumatic starter system. The groups were given FMEA and potential ICHM application boards, office supplies and materials in addition to their information books. Greg Colman provide revised FMEA and equipment hierarchy lists.

At the start of the second day (September 26) of the workshop all of the groups reconvened into one large group. Each group leader presented the results of their subgroup. The engine, reduction and accessory gearbox group found 26 items, which were recommended for monitoring. The generator group identified thirteen items. The ancillary group identified four items. The results of each group are summarized in Table 2, Table 3 and Table 4, respectively.

Following the presentations, a total group discussion was held to identify any overlaps in the analysis and also to identify relationships, which were important from the system level. The results of this discussion led to the identification that engine conditions and generator conditions should be monitored in an intelligent manner to distinguish between electrical and mechanical problems. It was learned during this discussion that sometimes electrical problems in the generator exhibit mechanical symptoms in the engine. Another important discovery was the relationship between multiple SSGTG's. Sometimes one SSGTG carries more than 50% of the load due to problems with the second SSGTG. Also, the ill effects of repeated preventative maintenance and training procedures were described as causing a number of operational failures. Finally, the reduction of PMS and performance monitoring (i.e. thermal efficiency) was identified as areas of opportunity for aiding in system troubleshooting and deciding when to perform maintenance (e.g.; water wash).

Following the discussion of system health issues, Bill Nickerson requested final comments regarding the technical content and structure of the workshop for The Good of The Order. Comments of participants are attached. The workshop adjourned at 1:00 p.m. September 26, 1997. These comments are included as Appendix D.

501-K34 Maintenance and Diagnostic Requirements WORKSHOP
Meeting Minutes

Table 1 - Attendees

Name	Organization	Phone/FAX	Email
Les Johnson	ARL Penn State	(814) 865-3913/3-0673	ldj1@psu.edu
Bill Nickerson	ARL Penn State	(814) 863-9899/0673	gwn1@psu.edu
Dr. Jeff Kohler	ARL Penn State	(814) 863-4491	jk9@psu.edu
Greg Colman	Allison Engine Co.	(317) 230-6288/3596	iegdc@agt.gmeds.com .navsea.navy.mil
Vern Holmes	Allison Engine Co.	(317) 230-5890	
Tom Stordahl	Allison Engine Co.	(317) 230-5067/3596	ietms@agt.gmeds.com
Chris Armitage	AMS	(757) 640-6413/6421	chris_armitage@mail. .amsinc.com
Ken Scandell	CHET Norva/PMS400F	(757) 444-1999/1017	scandell_ken@hq.navsea .navy.mil
LT Tom Tomaiko	CLF N434	(757) 322-3759	n434@clf.navy.mil
Tom Matella	CNSL Port Engineer	(757) 445-2175/1189	tmatella@force.cnsl.spear .navy.mil
Will Higgins	FTSCLANT 4335	(757) 444-4248	will_higgins@ftsclant .navy.mil
Al Mancuso	FTSCLANT 4335	(757) 444-4213	
Tien Phan	FTSCLANT 4313	(757) 445-4912/4910	tien_phan@ftsclant.navy .mil
Ron Trager	FTSCLANT 4321	(757) 445-4289	ron_trager@ftsclant.navy .mil
Scott Zerr	FTSCLANT 4311	(757) 445-4911	
Ben Wainscott	FTSCPAC 304	(619) 556-2639	wainscott_ben@ftsc-emh .ftscpac.navy.mil
Mike Mulkey	FTSC Det Mayport	(904) 270-5234	
Bill Masincup	NAVSEA 03Z34B	(703) 602-7120/9512	masincup_bil@hq.navsea .navy.mil
Jim Burns	NSWCCD 1113	(215) 897-7926/1674	burns@oasys.dt.navy.mil
Celena Cook	NSWCCD SSES	(215) 897-8746	cook@mailgate .navsses.navy.mil
Dick DeCorso	NSWCCD	(301) 834-4131/6931	dikdecorso@aol.com

501-K34 Maintenance and Diagnostic Requirements WORKSHOP
Meeting Minutes

Table 1 - Attendees

Jim Donnelly	NSWCCD 955	(215) 897-1152/1038	
Thom Galie	NSWCCD 941	(215) 897-7960/7600	galie@mailgate.navsses .navy.mil
Roger Nadeau	PMS 400	(703) 602-5981/7377	nadeau_roger_gses@hq.
Dave Thurston	ONR 351	(703) 696-4251	thurstd@onr.navy.mil
Alan Federovich	SURFLANT	(753) 322-3357/3258	afederovich@cnsl .spear.navy.mil
Steve Stephens	USS The Sullivans	(207) 776-6802	thedeco@aol.com
Florizel O'Hara	USS The Sullivans	(207) 776-6802	

Table 2. Engine, Reduction and Accessory Drive System Opportunities for Condition-Based Maintenance. (Cat indicates priority for demonstration as a part of the Accelerated Capabilities Initiative for Machinery Diagnostics and Prognostics)

Cat	Fault or Activity to be Addressed	Rationale	Proposed Approach
1	*Filter Assembly, Compressor Bleed Air (6873547)*	Problem events – clog without indication	Pressure
1	*Ignitor Assembly*	Problem events – ends burn	Electrical Characteristics Check
1	*Main Reduction Gearbox – Bearings (90-0300-08501, -08601, - 14101, -14102)*	Opportunity	Vibration and Acoustics, Data Fusion with Thermocouples
1	*PTO Mid Shaft Bearing (6871201)*	Problem events	Vibration and Acoustics
1	*Sensor – CIT (23007397)*	Problem events – Accuracy	Performance, Validity Check
1	*Shaft Gear, Accessory Main (6793309)*	Problem events – misalignment	Vibration and Acoustics
1	*Thermocouple Assembly*	Problem events – burning	Data fusion, Sensor Validity Check
2	Accessory Gearbox Bearings (6784737, 6784727)	Critical potential failure modes – opportunities	Vibration and Acoustics
3	1st Stage Compressor Blade (6809081)	Airfoil damage (FOD) events	Vibration and Acoustics, Performance
3	1st Stage Compressor Vanes (6876101)	Airfoil damage (FOD) events	Vibration and Acoustics
3	1st Stage Compressor Wheel (23053781)	Problem events – seal clearances and spacer failure	Performance, Vibration and Acoustics

3	1st Stage Turbine Vane Assembly (23006491)	Problem events – cracking and burning	Vibration and Acoustics, Performance
3	2nd Stage Compressor Wheel (6841210)	Seal clearance problems – cost	Vibration and Acoustics, Performance
3	Bearing – Radial Drive Shaft (2) 23030559	Problem events – corrosion and failure	Vibration and Acoustics
3	Bearing – Rear Compressor (6871643)	Problem events – corrosion and failure	Vibration and Acoustics
3	Bearing, Ball (6783727)	Problem events	Vibration and Acoustics
3	Bearing, Roller Cyl-Turb (23058594)	Problem event – corrosion	Vibration and Acoustics
3	Compressor Air Inlet Housing (6848669)	Problem events and costly events (seal leakage – loose PTO Shaft Housing)	Acoustics and Vibration
3	Compressor Case Assembly (23009769 and 6877133)	Problem events – split line leakage, blade tip clearance opening	Performance, Module Acoustic Level
3	Compressor Shaft, External Ball Bearing (6875356)	Problem events	Vibration and Acoustics
3	Front Compressor Labyrinth Seal (23008169)	Problem events – leakage	Vibration and Acoustics, Performance, Oil Consumption
3	Front Compressor Roller Bearing (23058591)	Problem events – corrosion and failure	Vibration and Acoustics
3	Front Turbine Roller Bearing (6849475)	Problem events – corrosion, failure	Vibration and Acoustics
3	Gear, Compressor Side (6827847)	Problem events – corrosion and failure	Vibration and Acoustics
3	Lighthouse Seal	Problem events – leakage	Vibration and Acoustics
3	Shaft, Compressor Extension (6783872)	Problem events – corrosion and failure	Vibration and Acoustics

Table 3. Electrical Generator and Control System Opportunities for Condition-Based Maintenance. (Cat indicates priority for demonstration as a part of the Accelerated Capabilities Initiative for Machinery Diagnostics and Prognostics)

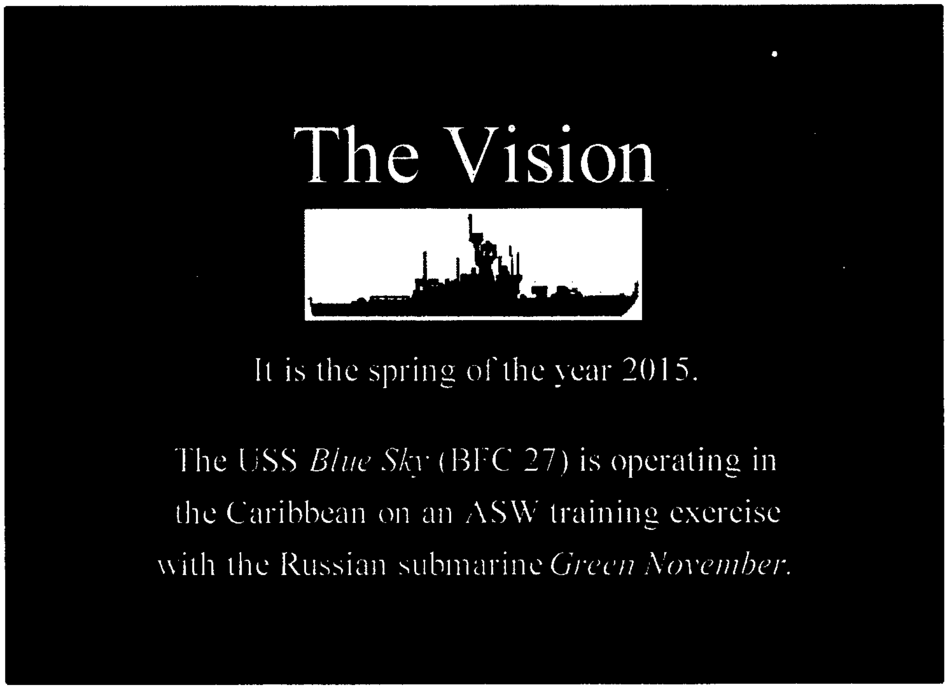
Cat	Fault or Activity to be Addressed	Rationale	Proposed Approach
1	*Generator Frequency Instability*	Frequency deviations can create problems in the power system loads, cause undesirable interactions between paralleled generators, and indicate problems in the engine and generator.	Install the capability to detect the problem, and to determine the underlying cause.
1	*Lamination Damage*	Lamination damage of the stator primarily occurs when the stack bolts loosen, or from mechanical damage when the rotor is pulled from the generator. Loosening or damage to the laminations result in intense local heating, which will cause deterioration and failure of rotor or stator winding insulation. This problem does occur, and although it is not real common, it will take the generator out of service for the duration of the mission, and it is very expensive to replace the generator.	Install the capability to detect lamination damage so that the generator can be taken off line before insulation systems are compromised.
1	*Performance Parameters (Engine Thermal Efficiency)*	The overall health of the GTG and electrical power system can be assessed by certain performance measures. Moreover, system-level problems could be identified.	
1	*PMS actions*	PMS actions can result in problems and failures, such as loose connections and damage to other components. The information gained from these PMS activities could be obtained through alternative means.	Install the capability to replace certain PMS activities.
1	*Stator & Rotor Insulation Failures*	Deterioration of insulation systems, turn-to-turn and line-to-ground, occurs as a result of thermal cycling, chemical contamination, mechanical damage, and overvoltage transients. The initial stage of deterioration does not create a problem, but increasingly will degrade generator performance. If growth of the defect is allowed to continue, a high-energy electrical fault will occur, resulting in serious damage to the entire generator. This problem does occur, and although it is not real common, it will take the generator out of service for the duration of the mission, and it is very expensive to replace the generator.	Install the capability to detect insulation deterioration, so that generator is not operated as it approaches the catastrophic point.
1	*Unequal Load Sharing*	The load should be shared equally, within specification, between generators. If it is not, there is a problem, ranging from the fuel nozzles to the electrical control circuits. Although it is not likely that this will damage the electrical generator, the underlying problems could eventually take a generator out of service.	Install the capability to detect the problem, and to determine the underlying cause.
1	*Fan Failures*	Balance and structural problems of the fan can result in pieces of the fan breaking off, and then damaging the generator and creating a safety hazard.	Install the capability to detect fan unbalance before a failure becomes imminent.

2	Electrically-Excited Vibration	Certain electrical problems will result in structural vibrations that mimic those of mechanical origin. This can result in unnecessary efforts, such as bearing replacements, and if uncorrected the vibration can cause other mechanical problems.	Install the capability to distinguish between mechanically and electrically excited vibrations.
2	Grounds in Control Circuits	Unintentional grounds within the control circuits represent hidden faults that can cause many things from operational problems to serious damage.	Install the capability to detect control circuit grounds.
2	Ignitor Assembly - Tip Wear	As the ignitor elements wear, their performance deteriorates until there is a problem. Although this does not result in an electrical problem, it may be detectable by analyzing the electrical inputs to theIgnitor assembly.	Install the capability to detect wear in the ignitors.
3	Air Cooler Failure	Reduced performance or failure of the cooler will result in overheating of the generator windings, which can necessitate taking the generator off-line, or if unchecked can cause a winding failure.	Install the capability to detect reduced coolant flow through the air cooler.
3	Electronic Board Failures	Failures of electronic components, including circuit cards, create a variety of problems. However, detection of localized electronic failure at the ICHM level is impractical. It is possible to monitor board inputs and outputs to diagnose a failure, but there appears to be minimal benefit to do so at this time, given the implementation problems of doing this. Nonetheless, it would be beneficial to detect the presence of a problem, at the system level, so that a manual diagnostic effort could be initiated.	Install the capability to detect changes in the output of the No-Break Power Supply output that are indicative of load-side problems.
3	Fuel Assembly Control (governor)	The engine will not start or operate properly if the governor fails, and the cause of this can be electrical in nature. More often than not, the problem is of a non-electrical origin.	Install the capability to monitor and evaluate each of the five process variables of the governor.
3	Loose Connections	Connections that loosen from mechanical vibration, or those that are not properly tightened during a maintenance action, overheat. This can result in thermal damage, fire, and arcing within a confined space.	Install the capability to detect loose connections.
3	Pedestal Bearing Failure	Failure of either pedestal bearing allows the rotor to collided with the stator, resulting in catastrophic damage to both the rotor and stator. This problem is relatively uncommon, but it will take the generator out of service for the duration of the mission, and it is very expensive to replace the generator.	Install the capability to detect bearing deterioration prior to failure.

Table 4. Ancillary Systems Opportunities for Condition-Based Maintenance. (Cat indicates priority for demonstration as a part of the Accelerated Capabilities Initiative for Machinery Diagnostics and Prognostics)

Cat	Fault or Activity to be Addressed	Rationale	Proposed Approach
1	*CDP Transducer*	Lack of output leads to underspeed shutdown. Troubleshooting is time consuming to find failed transducer.	Instrumentation of transducer to alert operator to failure would improve trending analysis and expedite system troubleshooting.
1	*Fuel Nozzles*	Blockage or coking of nozzles creates hot spots. Problem has been corrected through increasing the drain line size to eliminate residual fuel and through nozzle design.	Propose that instrumentation of individual thermocouples be designed as input to ICAS to determine exact hot spots should nozzles clog and to monitor thermal efficiency of engine for long-term evaluation and fuel efficiency.
3	Lube Oil Cooler	Due to corrosion problems in the single tube design, contamination with seawater becomes a problem for the lube oil system. This deficiency is a design problem that is currently under consideration and should be corrected within the next 8-10 months. However, the new design alternatives still are a single tube configuration thus the probable contamination situation still exists.	Propose the investigation of incorporating a salt, moisture, increase oil temperature (blockage), or viscosity change sensor (if possible) to alert operator to onset of contamination before damage can occur.
3	Pneumatic Starter	Moisture in air system for pneumatic start is a real problem. Centrifugal separator exists to eliminate this problem but is often not used.	To avoid problems associated with erratic starter operation due to moisture, propose a moisture sensor be installed to indicate moisture presence and placed in series with the starter actuation until moisture level is resolved.

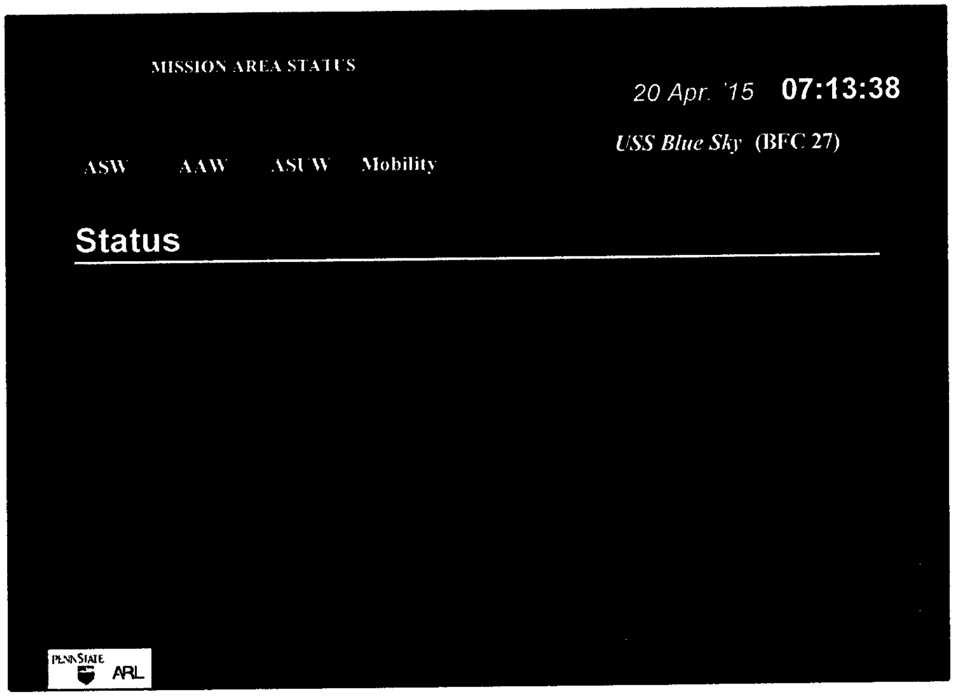
APPENDIX A



This story represents a view into the future when the results of ongoing research in Condition-Based Maintenance have yielded a reliable and effective machinery prognostics capability.

This capability along with advanced monitoring system technology, decision support, and human computer interface advances provides a dramatically different approach to fighting a ship.

The details of the implementation are notional and are put forth for consideration. There is no intent to establish doctrine. The division of responsibility presented is chosen because is differs from current doctrine and is feasible. The system envisioned would be flexible enough to support any desired division of responsibility tailored for the particular ship and crew and perhaps even for the situation.

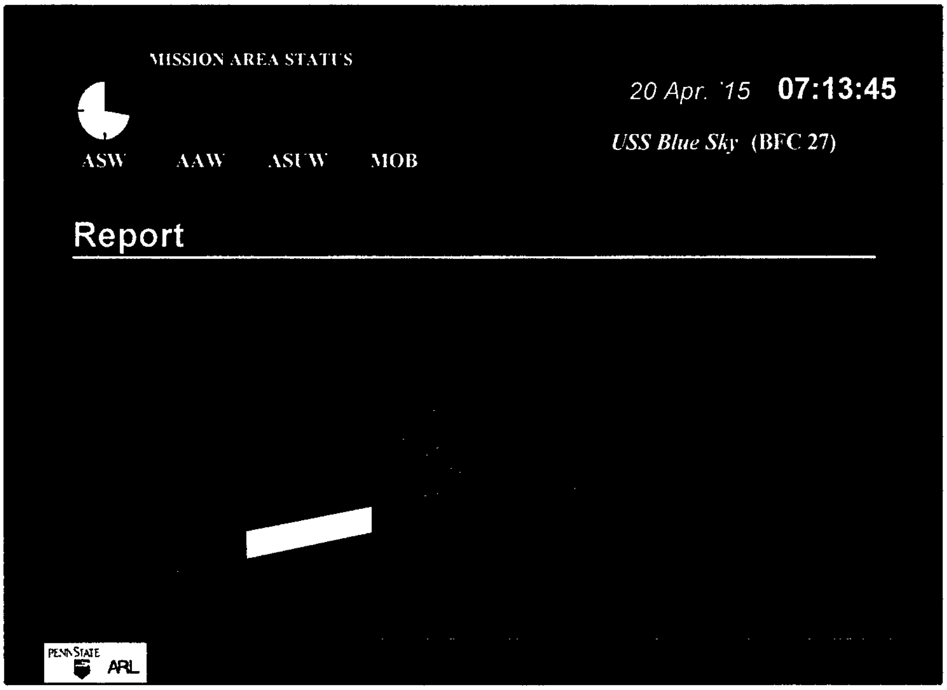


It is about 0715 in the spring of 2015. The Captain is on the Bridge viewing the "top-level" ship status display.

Indicators are shown at the top for each of the ship's "mission areas".The color of each is green indicating that the ship is fully mission capable for the planned mission duration.

The fact that the mission indicators are not fully colored in indicates that there is some degradation, but within bounds for fully mission capable.

The depiction of the ship gives a topological view of the platform and again shows that there are no problems requiring attention within the mission horizon.

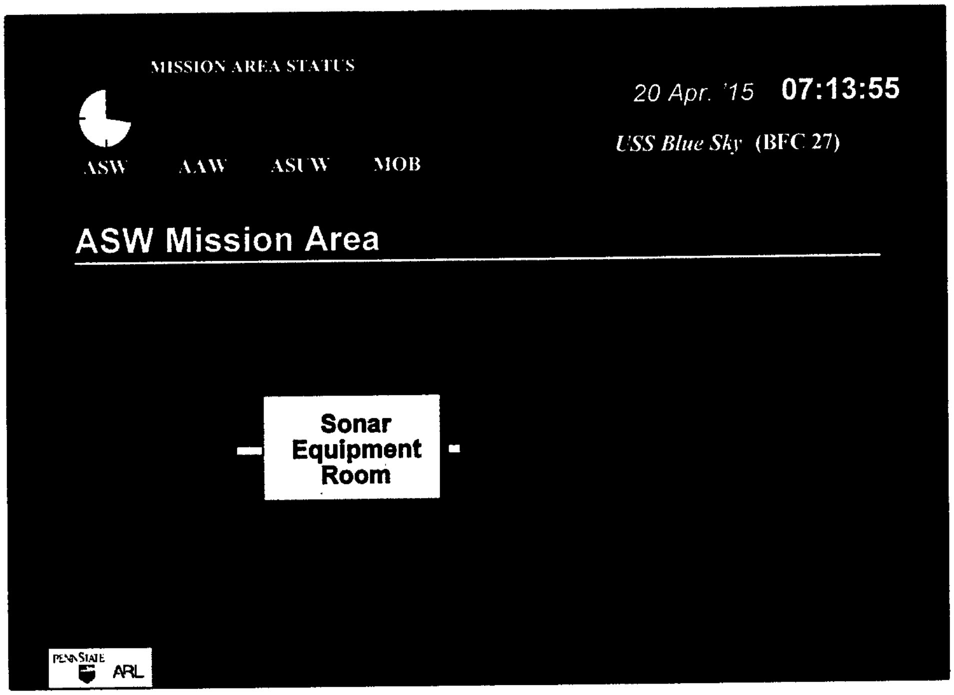


While the Captain is viewing the screen, the ASW mission area turns yellow as does a section in the forward portion of the ship.

A yellow indication tells the Captain that a condition has evolved that is not an immediate alert, but has the potential of impacting the ability to prosecute the mission within the mission horizon.

Since the ship is involved in an ASW mission, the Captain decides to investigate the situation personally.

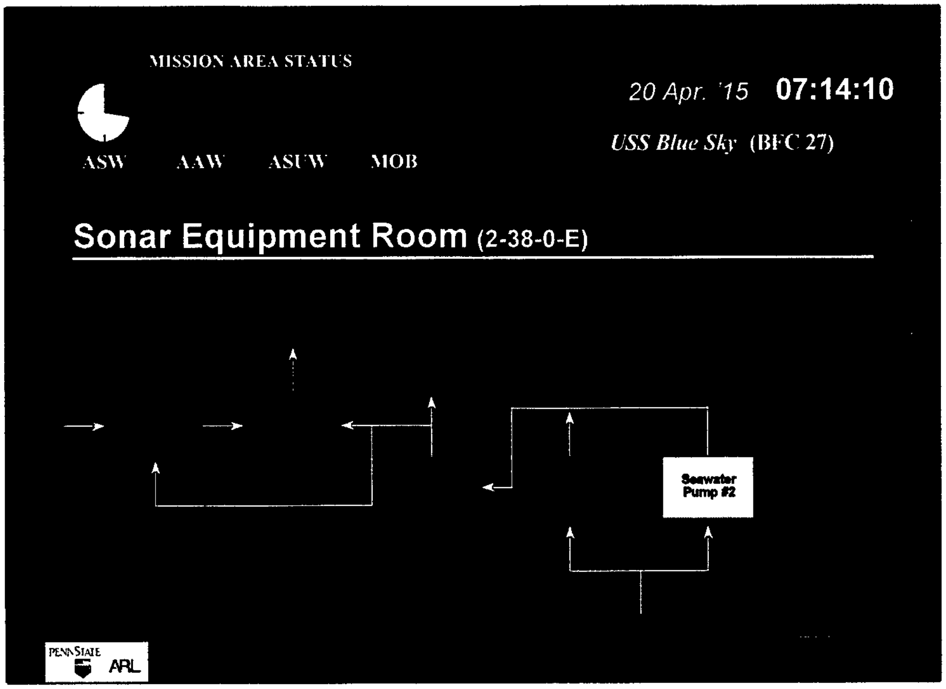
The display is touch sensitive, so a touch to the ASW Mission Area Indicator starts the investigation.



The Captain is presented with a block diagram of the primary elements of the ASW Mission Area.

Clearly the Sonar Equipment Room is the culprit.

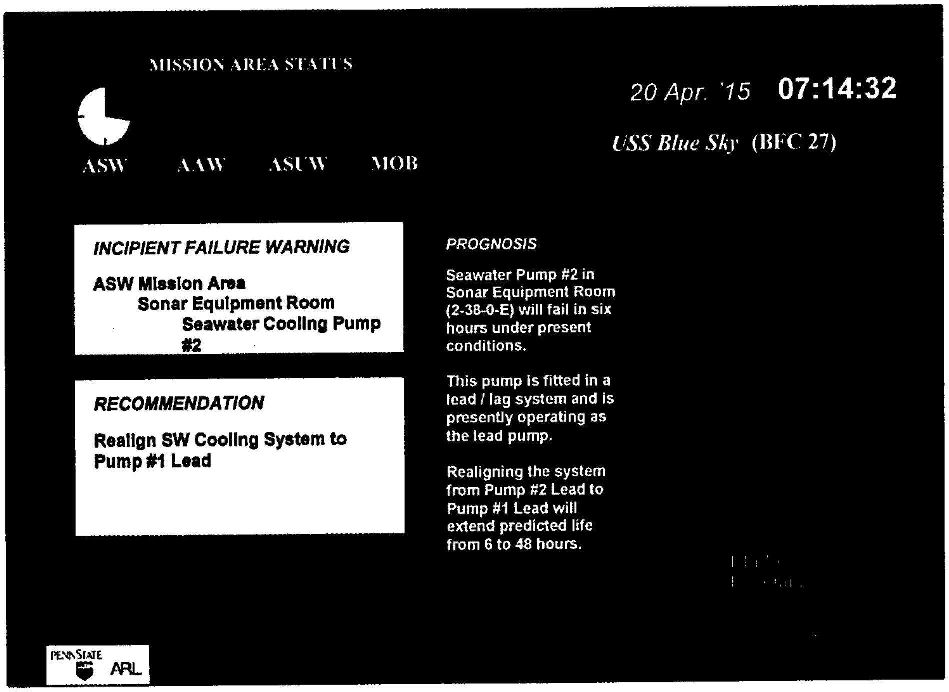
A touch to the Sonar Equipment Room block brings up the next screen.



The Captain is presented with another block diagram, this time of the equipment in the Sonar Equipment Room. Note that if the Captain had touched the yellow cell on the ship topology display, this screen would have been immediately presented.

Clearly the evolving problem is in "Seawater Pump #2"

A touch to the "Seawater Pump #2" block brings up the detailed display of the problem.



In this display, the Captain is presented with a detailed situation report. The incipient failure warning shows that the ASW Mission Area is affected by an incipient failure of Seawater Pump #2.

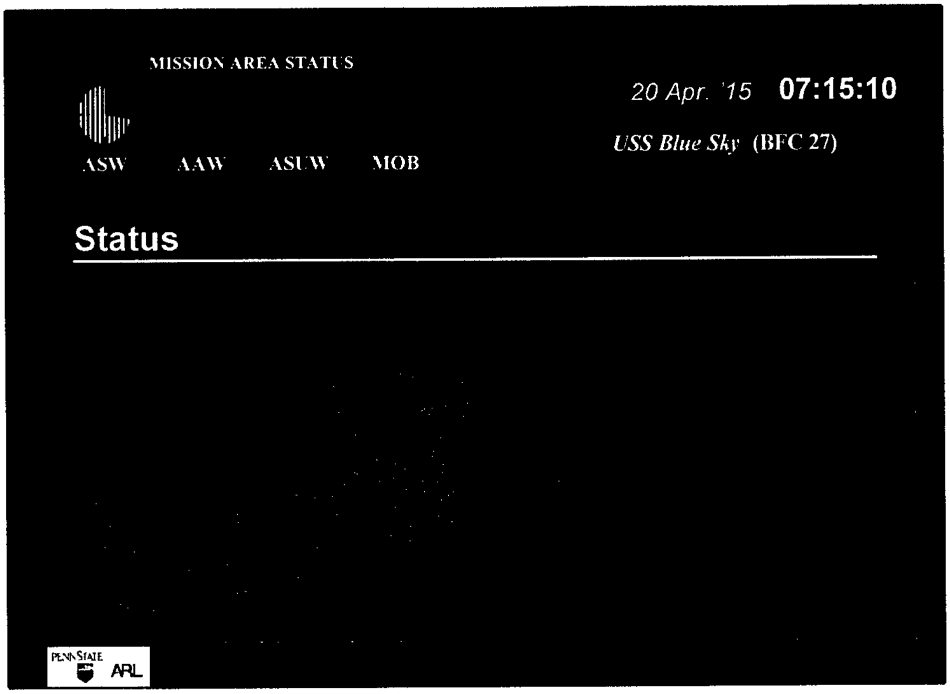
The Prognosis window shows a detailed assessment of the condition and an alternative that enables the mission to be completed without compromise.

The Recommendation window provides an option to be considered by the Captain that is determined by the system to be the highest probability, minimal impact action to continue the mission within prescribed limits of certainty.

The Accept and Defer buttons provide the opportunity to immediately implement the recommendation or to defer on the decision pending further investigation or action by the Chief Engineer.

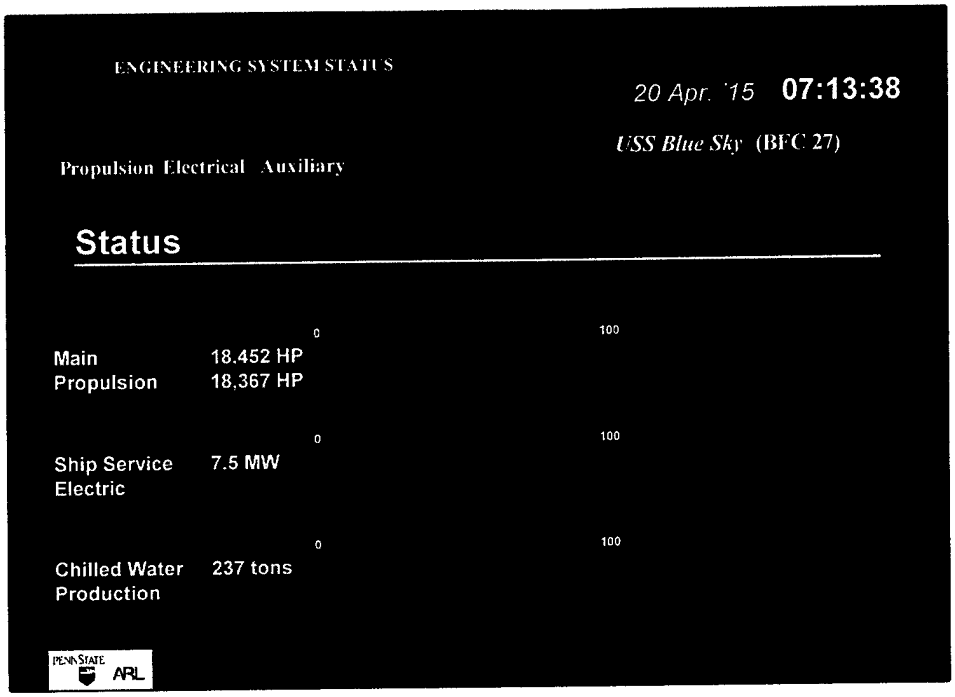
In this case, the alternative proposed is simple and can be automatically implemented. The Captain chooses to Accept the recommendation by pressing the Accept Button.

This returns the Captain to the top-level ship status display.



The Captain can now confidently continue the mission without being concerned about the incipient failure in Seawater Cooling Pump Number 2.

Note that the ASW Mission Indicator is still yellow, but cross-hatched. This indicates that the problem is still active, but that it has been dealt with. The color of the Sonar Equipment Room on the ship topology display has changed with the same implication.

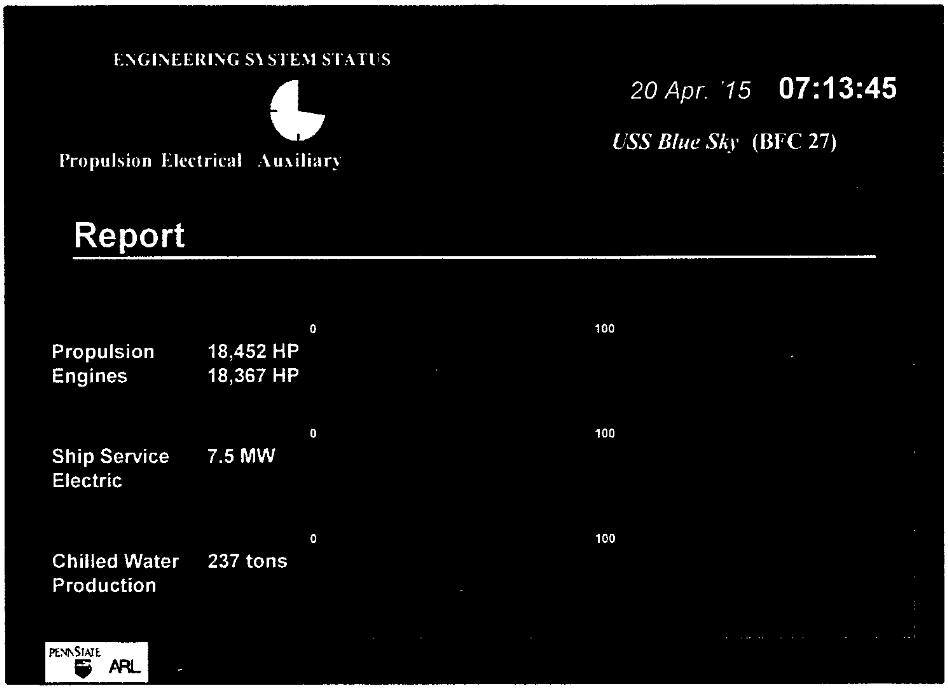


Meanwhile in the Log Room, the Chief Engineer (CHENG) is viewing the top level Engineering System Status display.

Shown in a similar color coding scheme are the Engineering System Status indicators and fully customizable indicators of the status of the major engineering subsystems; in this case indicating the production levels of major services relative to full capacity.

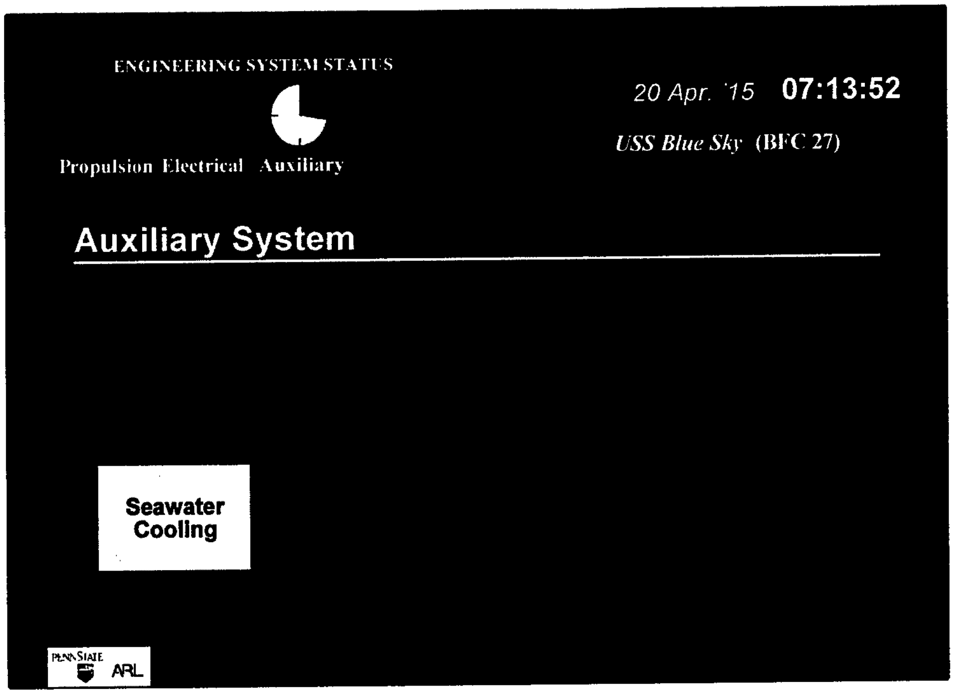
All engineering systems are indicated by their green color to be projected to continue to operate without unplanned attention for the duration of the cruise.

Note the difference in time horizon of interest between the Captain and the CHENG. The Captain is immediately concerned only with completing the mission at hand while the CHENG is concerned with the long term performance of the engineering systems.



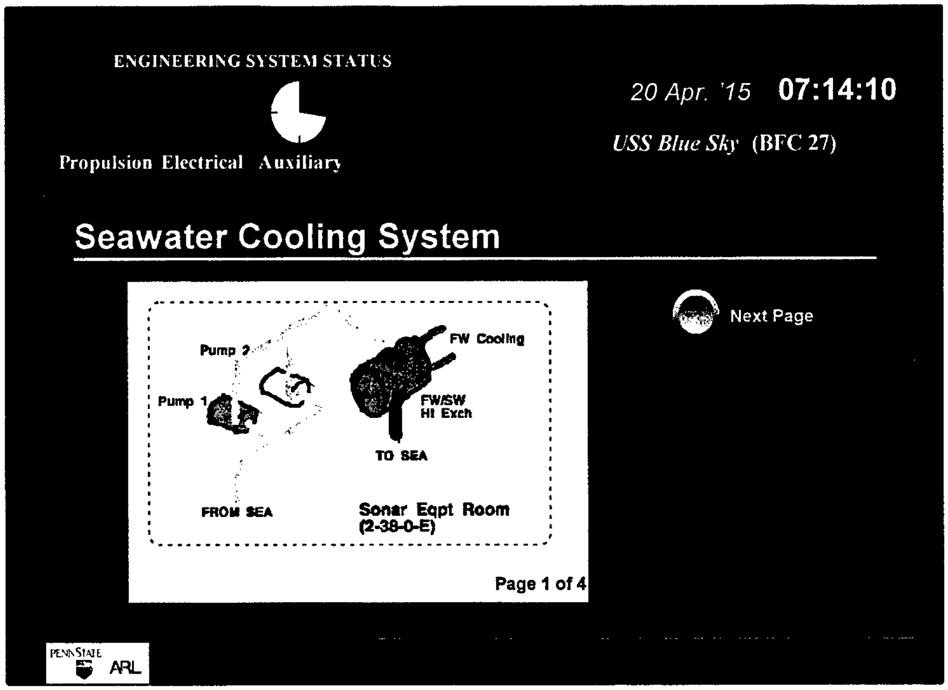
At the same time as the Captain's ASW mission indicator turned yellow, the CHENG's Auxiliary System Status indicator turns yellow. This has the same implications to the Engineer as the ASW Mission Indicator did to the Captain.

The CHENG touches the Auxiliary System Status Indicator to further investigate.



The CHENG is taken to a display of the Auxiliary Subsystems. In this case, Seawater Cooling is clearly the culprit.

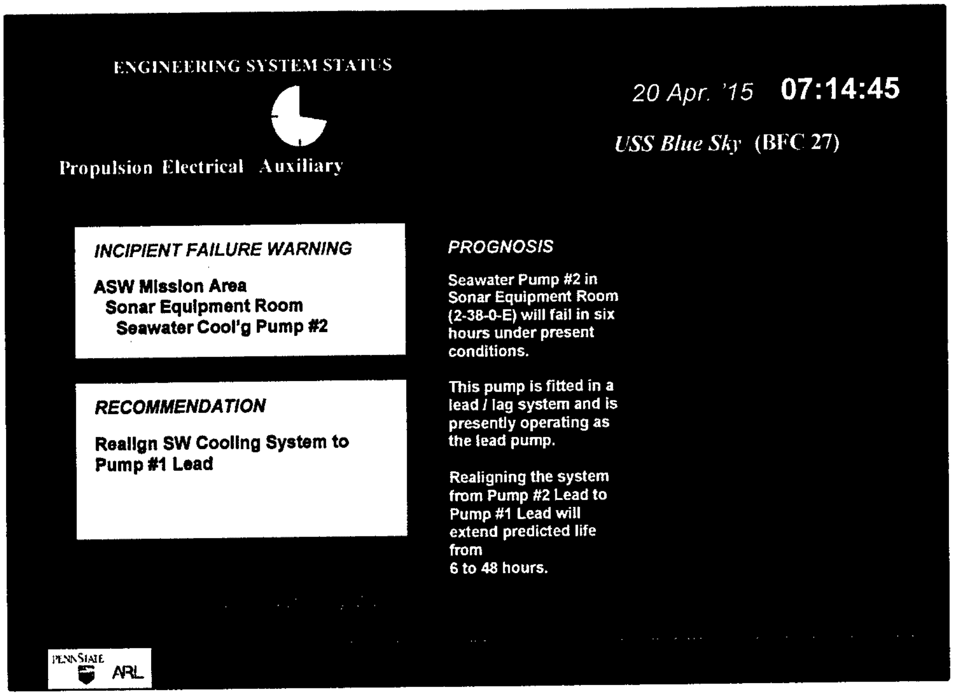
Touching the Seawater Cooling block takes the CHENG to the next more detailed view of the situation.



For the CHENG, a pictorial display of the Seawater Cooling system in the Sonar Equipment Room is most appropriate. Clearly Pump 2 is the equipment requiring attention.

The "Next Page" button allows the CHENG to browse through the other three pages representing the Seawater Cooling System.

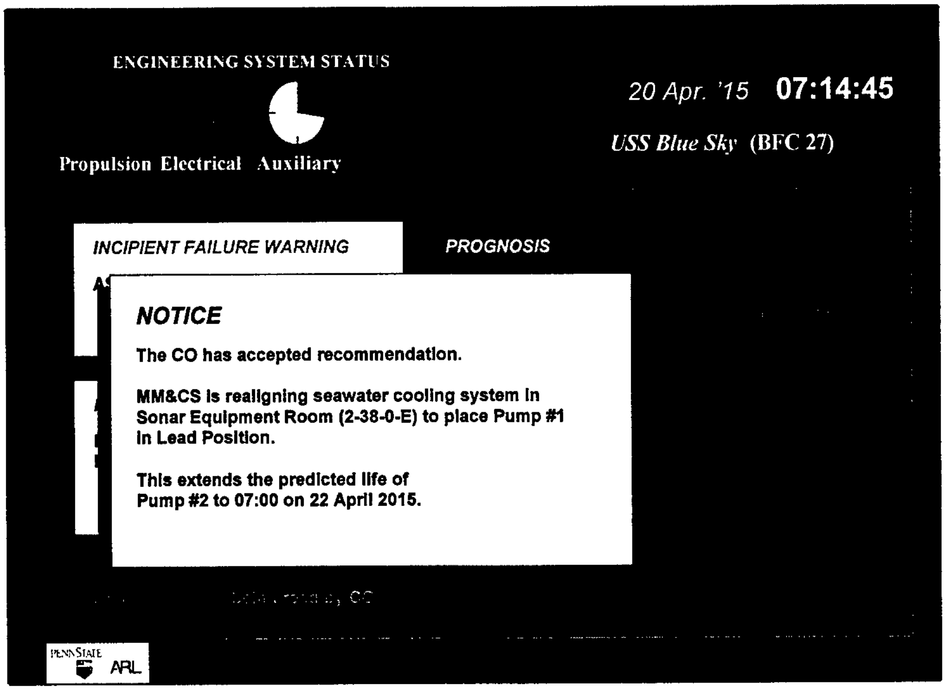
Touching the Pump 2 Icon brings up a detailed situation report.



The CHENG has now arrived at the same page as the Captain, but by an entirely different path. In this case, the Captain is viewing the page and has the opportunity to take a decision to accept or defer on the recommendation.

While that decision is being made, the CHENG may not act on the recommendation. The Accept and Defer buttons are not operational.

The *BLUE SKY* and *GREEN NOVEMBER*

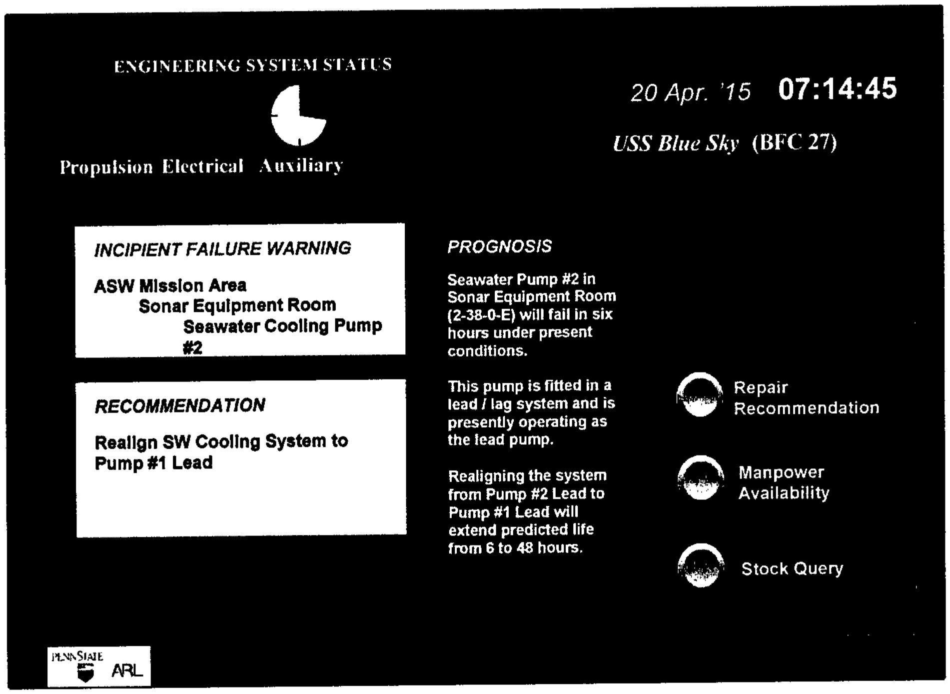


The Captain has chosen to Accept the system recommendation and the Machinery Monitoring and Control System is in the process of realigining the seawater cooling system appropriately.

The predicted life of the pump is thus extended past the current mission horizon.

The CHENG acknowledges this and proceeds to plan the repair that is necessary to maintain the ship in its fully operational state beyond the current mission.

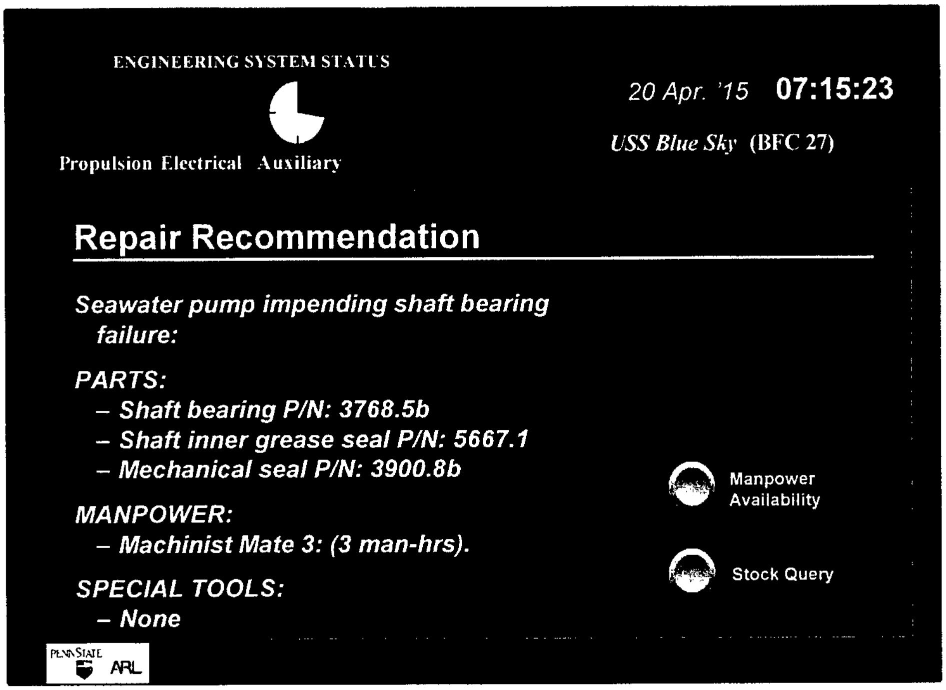
The *BLUE SKY* and *GREEN NOVEMBER*



The CHENG is presented with three options to start the repair planning process:

- Repair Recommendation - What should be done?
- Manpower Availability - Who should do it?
- Stock Query - Do I have the materials on board to complete the repair?

The first logical step is to review the Repair Recommendation by pressing that button.

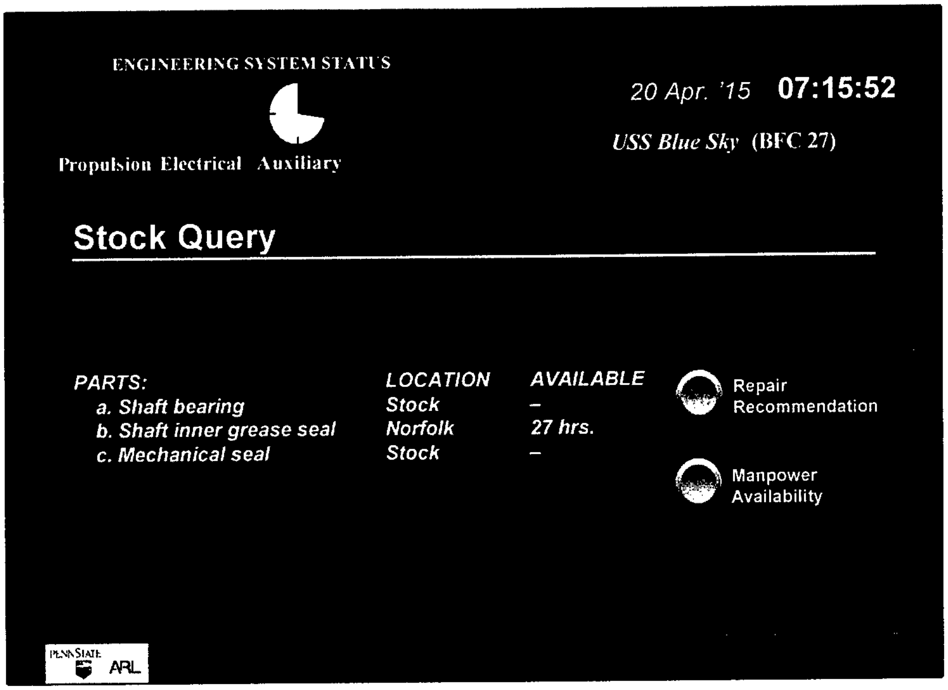


The CHENG is now shown that the Impending Shaft Bearing Failure on Seawater Cooling Pump number 2 requires a new bearing, a grease seal, and mechanical seal.

The repair will require a 3rd Class Machinist Mate 3 hours to complete.

No special tools are required.

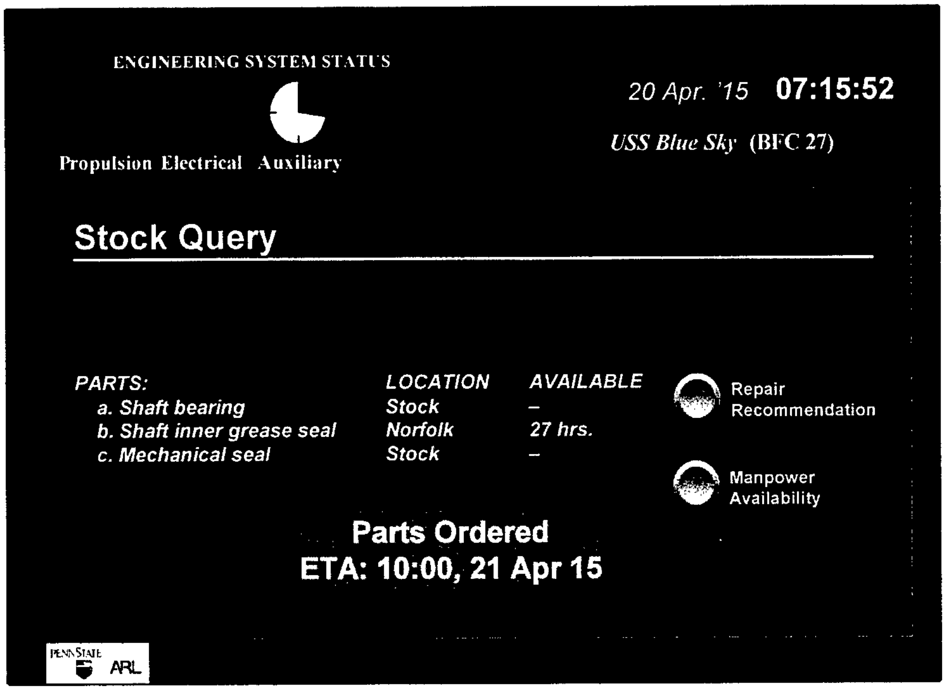
Next the CHENG chooses to find out the parts status.



As one might expect, one of the parts is not available onboard, it is stocked in Norfolk.

Since the Navy now has daily air freight delivery to all ships, the part can be delivered tomorrow morning.

The CHENG is given the opportunity to order the parts and arrange for their delivery by selecting the Order Parts button.

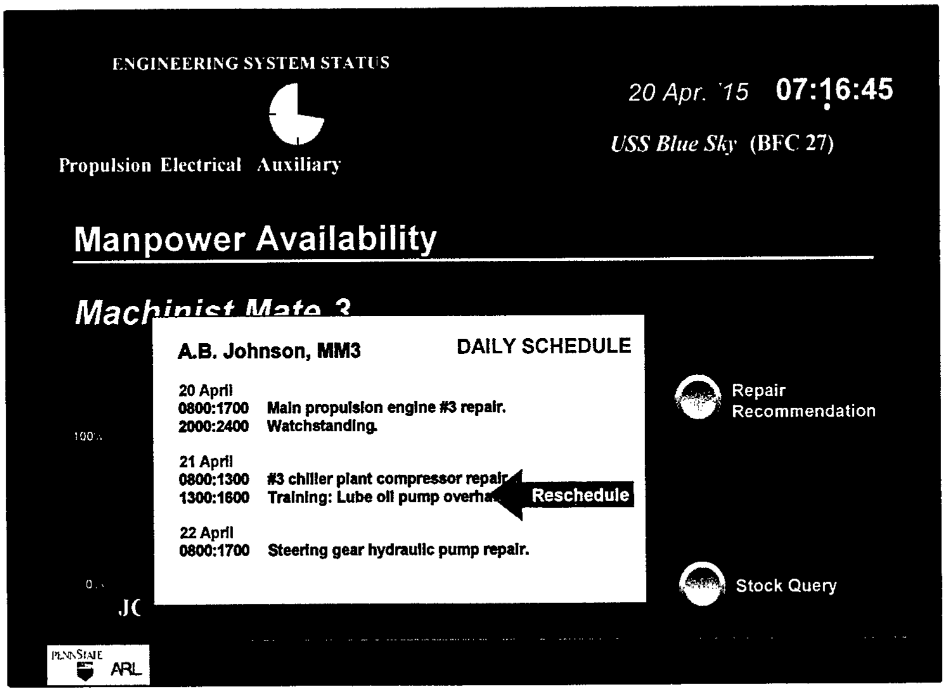


The Parts have been ordered and their delivery scheduled for 10:00 tomorrow morning - in time to complete the repair before the pump fails.

The CHENG must now assign responsibility to the person who will fix the pump by selecting Manpower Availability.

A schedule status chart is shown for all 3rd Class Machinist Mates. As would be expected, all are fully scheduled for the next 48 hours.

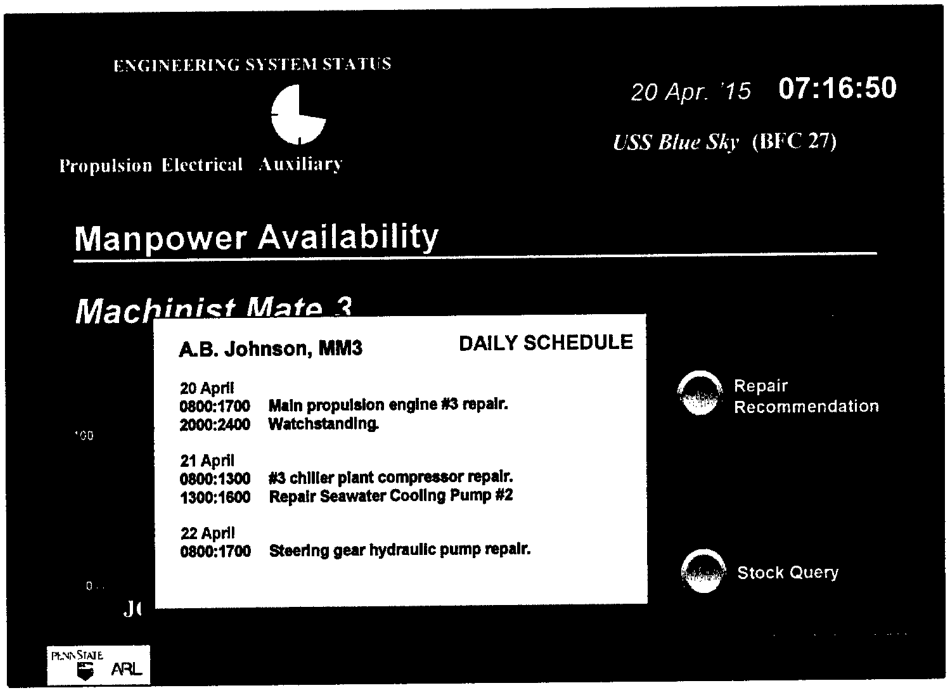
Johnson is the most experienced in seawater cooling pumps. Since this is an important repair affecting the current mission, the CHENG selects his schedule by touching the bar in the schedule status chart.



Johnson's detailed schedule for the next three days is shown.

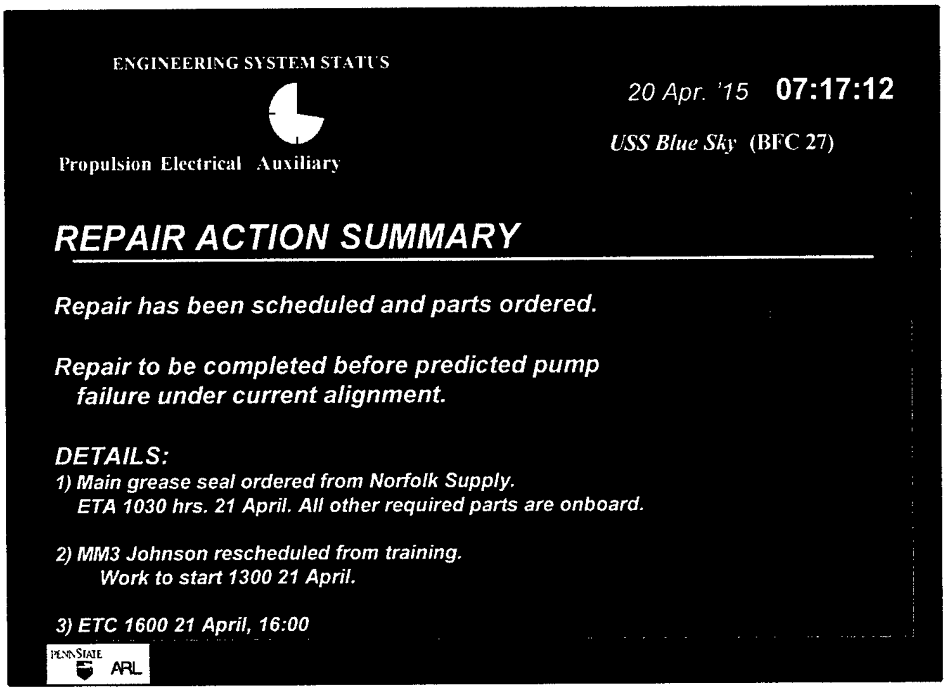
The system is recommending that computer-based training on Lube Oil Pump Overhaul is the best opportunity for Johnson to conduct the repair considering time of predicted failure, arrival of necessary parts, and ability to reschedule that training opportunity.

The CHENG could select the Reschedule Arrow and move it to another schedule item, but in this case chooses to accept the system's recommendation and reschedule the training by pressing the Reschedule Button.



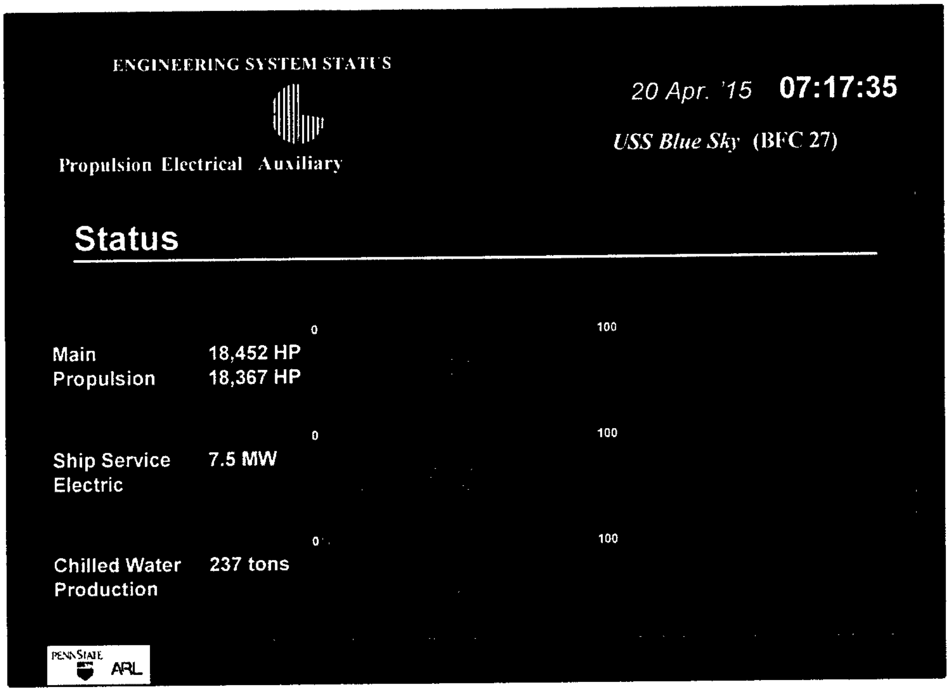
Johnson's revised schedule is shown indicating the new assignment for tomorrow afternoon.

The CHENG acknowledges the revision and is presented with a Summary for review.



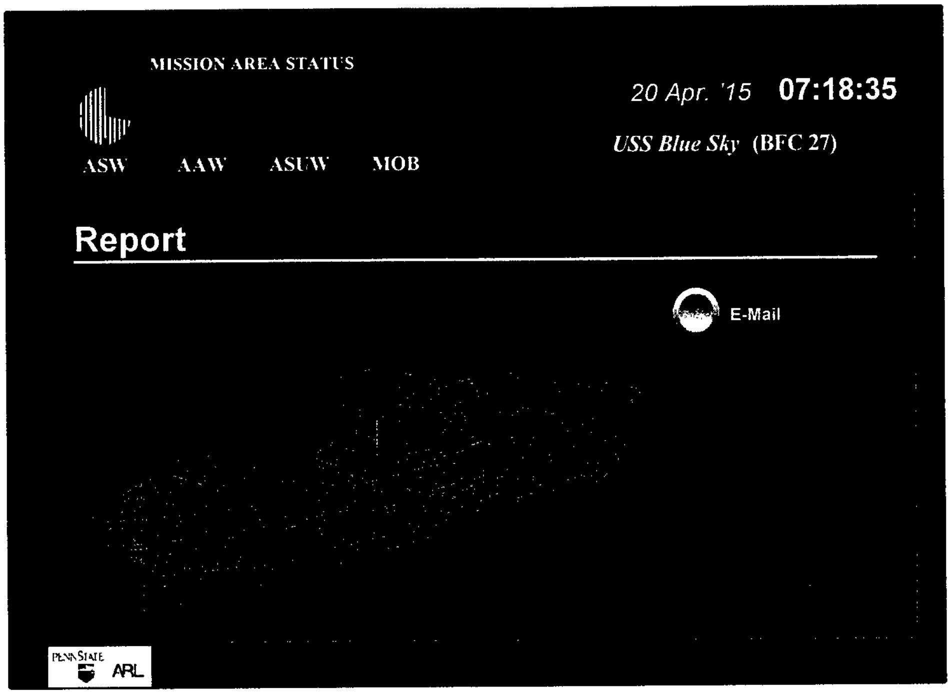
This summary shows that the necessary repair action is scheduled and that the necessary resources will be in place to complete the repair before it impacts the mission.

The CHENG acknowledges this plan and returns to the Top Level Engineering System Status display.

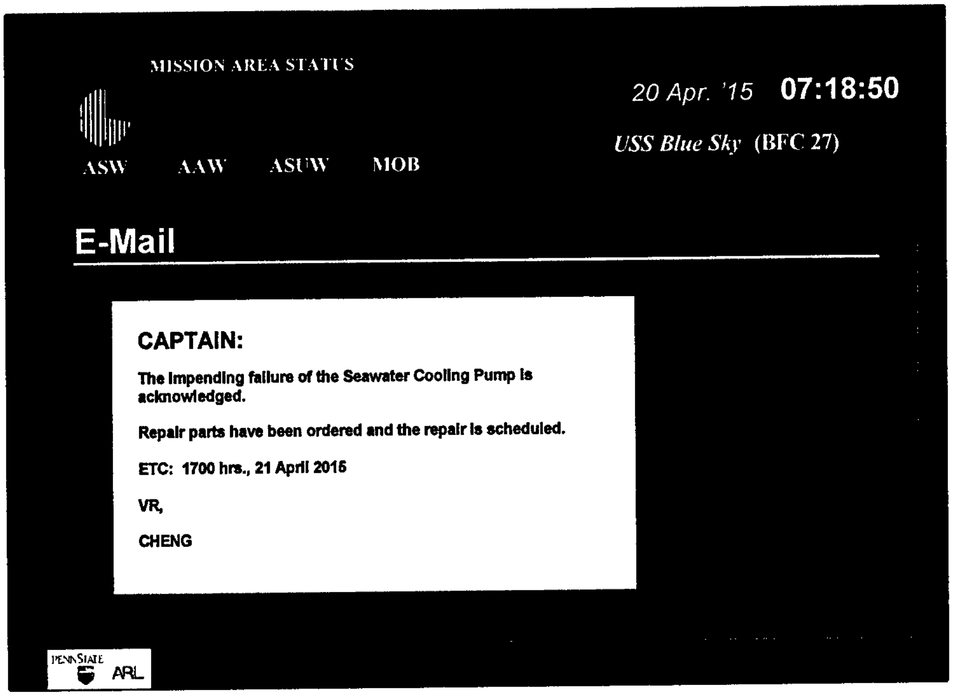


Similar to the Bridge Display, the Auxiliary System Status Indicator is cross-hatched to show that there is a problem, but that it has been dealt with.

The CHENG can confidently return to his daily activities knowing that the ship systems will continue to provide the necessary services to successfully complete all missions assigned.



Meanwhile back on the bridge, the Captain receives an e-mail message and presses the button at a convenient time.



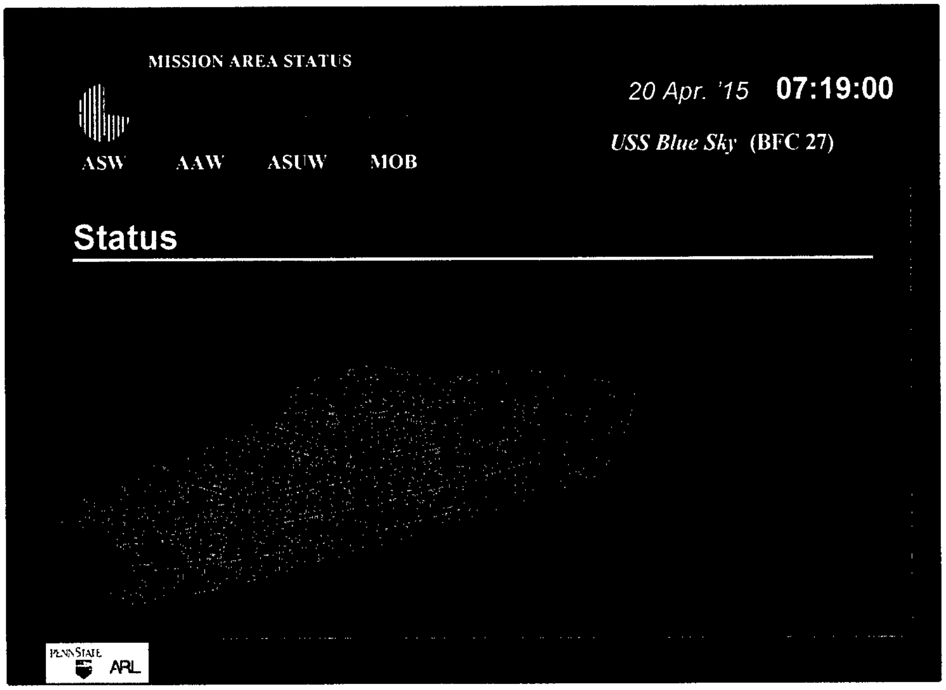
The e-mail is from the CHENG, but was automatically generated by the system in accordance with preset guidelines by the CHENG.

This message verifies that the impending failure has been fully dealt with and that it poses no impact to current or future missions of the *Blue Sky.*

Note that the system has added an hour to the Estimated Time to Complete (ETC) showing it as 17:00 vice the 16:00 actually planned. In this case the CHENG has directed the system to provide an hour of cushion between the actual planned completion and the report to the Captain since this extra hour has no impact on the mission.

The Captain acknowledges this message and returns to the top-level Mission Area Status Display confident that the ship systems will be able to complete the current mission.

The *BLUE SKY* and *GREEN NOVEMBER*



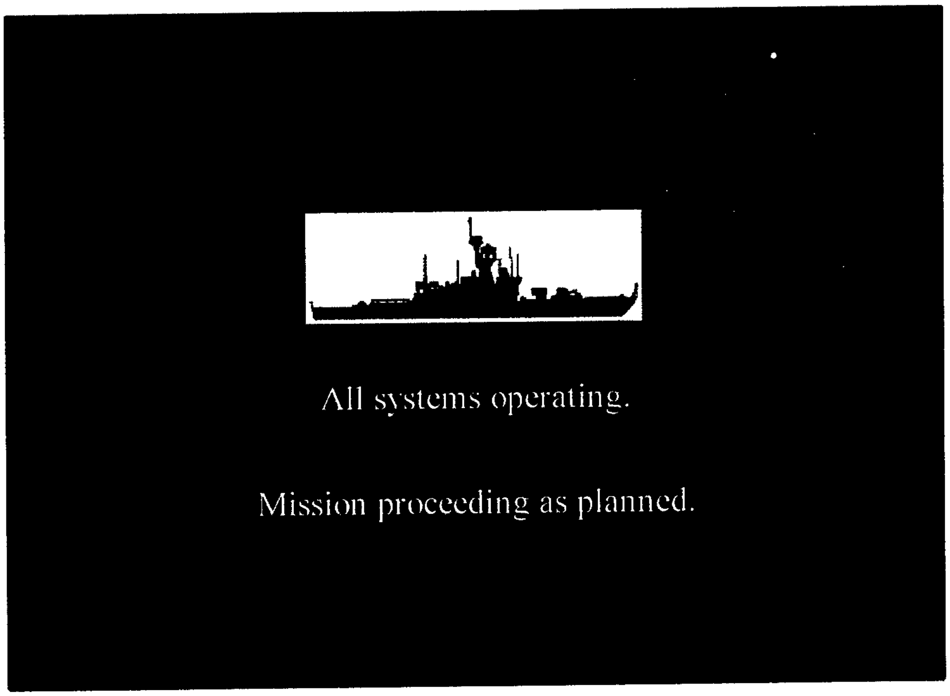
The Captain continues to pursue the *Green November.*

The entire evolution presented took less than 5 and 1/2 minutes in *Blue Sky* time! What would a similar evolution require today?

An important aspect of the capability envisioned for the *USS Blue Sky* is not presented. Johnson will have fundamentally different tools to conduct the repair to Seawater Cooling Pump #2.

- He will know precisely what the problem is before tearing the pump down or even entering the space.
- He will have direct access to electronic repair instructions in a user-friendly format actually useful in the machinery room of the ship.
- He will also have the ability to interact with experts throughout the globe in real time directly from the pump room through "tele-presence".
- He will have a built-in quality assurance on the repair from the embedded diagnostic/prognostics for the pump that will prevent the "maintenance induced failures" currently prevalent in equipment repairs.

The *BLUE SKY* and *GREEN NOVEMBER*



The scenario presented is simplified and has actions built into it that are inconsistent with current doctrine. It is not, however, technically infeasible.

The only thing that could not be done with current technology is predict whether the pump would fail in 6 or 48 hours under either lead or lag operating conditions. The prognostic technologies do not exist.

The monitoring, display, decision support, and automated interface to the supply system aspects of the story are all possible with today's technology. That they are not presently implemented is the result of two constraints:

> The current technologies in monitoring, communication, and display are too expensive to enjoy widespread implementation.
>
> The need for investment in making these systems a reality has not been compelling because it has only been presented as incremental change to current activities.

The ability to provide the type of prognostic information and change the way repairs are planned may provide a part of the justification. But, the decision makers must also recognize that it is not sufficient to automate current functions. These technologies offer an opportunity to fundamentally change the way the Navy, mans, fights, and maintains ships. It is this fundamental change that will drive the development of these technologies.

Current efforts to reduce manning may provide the necessary and sufficient condition to justify development and implementation of these capabilities.

I hope this story provides a basis for discussion of alternatives and issues.

APPENDIX B

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Condition-Based Maintenance

Prepared for:

ACI RCM Workshop

Presented by:

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Bill Nickerson is the Head of the Condition-Based maintenance Department at Penn State Applied Research Laboratory. He joined ARL in 1993 after working for the Navy at the David Taylor Research Center in Annapolis, MD for 15 years.

His background is in shipboard auxiliary machinery design and development and condition-based maintenance research. He has been active in developing the research program at the Office of Naval Research from its inception as a Logistics Block Program project in the late 80's.

The CBM Department at ARL is responsible for a variety of programs ranging from basic research through application in a variety of platforms from ships to amphibious vehicles to rotary wing to fixed-wing aircraft.

Bill holds a B.S. in Civil Engineering from Penn State and two Master's of Science in Engineering degrees from the University of Michigan in Mechanical Engineering and Naval Architecture & Marine Engineering.

“Preventive Maintenance

Doesn’t

(prevent maintenance)”

MGEN Mike Williams, USMC
Commander, MARCORSYSCOM
21 August 1996

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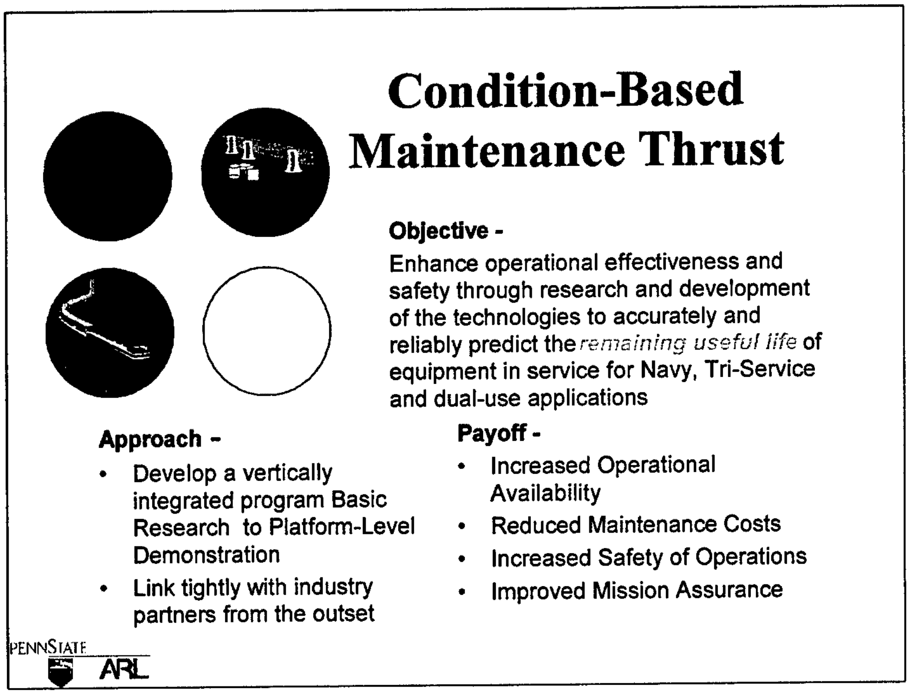
This one statement explains one of the major motivators for maintaining equipment on-condition.

MGEN Williams said this on a visit to Penn State ARL in August 1996. He referred to the frequency with which we make matters worse in undertaking preventive maintenance actions in the discussion that followed this quote.

One major benefit of NOT doing time-directed preventive maintenance is avoiding the problem or “maintenance-induced failures”. Numbers as high as 80% have been quoted as the fraction of total failures attributable to mis-assembly or damage during a preventive maintenance action. Clearly the best thing you can do for a machine that is running well is to leave it alone. Thus, the reasoning to “continuously” monitor the health of operating equipment and base maintenance decisions on a concrete indication of impending failure.



The overall objective of the work is to move "maintenance" from the logistics time frame (longer term planning) and move it into the operational time frame where real decisions about which equipment to employ are based on realistic and reliable measures of that equipment's health and likelihood of completing the assigned mission.

This capability would have significant impact on operational decisions, safety, and also reduce maintenance expenditures dramatically.

Achieving this objective will require basic research into the "science of failure" and a concurrent engineering approach to development that involves the equipment manufacturer from the outset.

This technology is inherently "dual-use". Maintenance problems in the military are no different from those in the commercial sector. Both have missions to complete whether that is transporting troops across the beach or delivering a time-critical shipment of automobile parts to a "just-in-time" manufacturing line in Detroit. Failure during the course of a mission is unacceptable.

Reliability Centered Maintenance

- Process for defining the maintenance requirements of equipment systems - IT IS NOT A MAINTENANCE PHILOSOPHY!
- Steps in RCM:
  - Hierarchical decomposition (functional) of plant
  - List functions with performance expectations
  - For functions, describe all ways the asset can fail
  - Describe ways in which mode manifests itself
  - Apply "RCM Logic" to categorize consequences and identify recommend maintenance action

From GasTOPS CaseFILE December, 1995, M. Tobin

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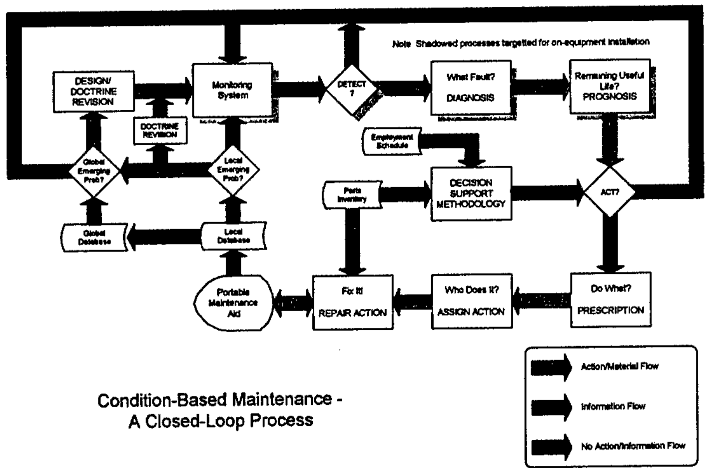
Reliability-Centered Maintenance was developed by United Airlines working with the FAA and Boeing aircraft in the late 60's to address the problem with scaling maintenance practices from previous aircraft to the wide bodies entering the fleet. A rigorous process was required to base maintenance decisions and practices on a rational basis. The concept of "applicable and effective maintenance actions" evolved.

RCM is not in itself a maintenance philosophy, it is a process to determine the proper combination of time-directed, corrective, and condition-directed maintenance tasks in your maintenance program. Frequently, maintenance programs developed using RCM processes are characterized as RCM, but this is an improper use of the term as originally described.

The steps in an RCM analysis shown will result in a practical and rationally justified maintenance program. The problem with traditional RCM is that it was designed long before the advent of the computer and communication technology available today.

Part of our program is targeted to update the RCM process to enable the decision to move to a condition-based maintenance program for the majority of equipment items to be made more rationally using the latest practical technologies. The general steps of the RCM process apply, it just requires altering the weighting factors at decision points.

CBM is a Closed-Loop Process



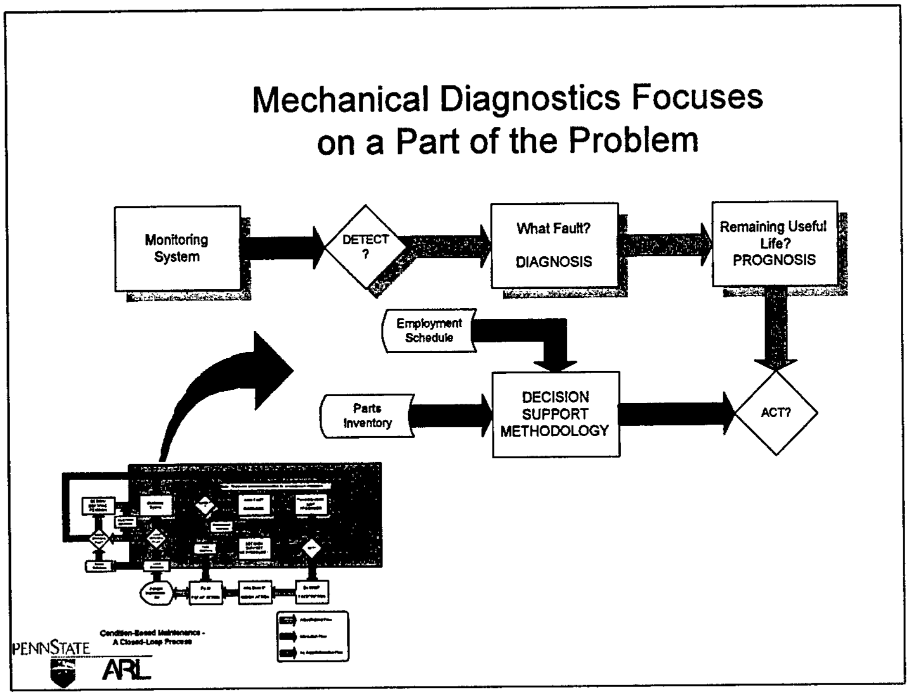
Condition-Based Maintenance -
A Closed-Loop Process

Condition-Based Maintenance as we describe it is a closed-loop process encompassing the entire operational cycle of a system.

The process starts with monitoring (including human observation) a system to first detect an incipient fault, diagnose what the fault is, predict the remaining useful life of the equipment item and support a decision to act. These items represent the key elements of mechanical diagnostics and is explained in more detail elsewhere.

Important other parts of this process include deciding what action to take (prescription), assignment of the human resources to take the action, executing the necessary action, capturing the knowledge gained during the action, distributing that to local and global databases, and monitoring locally for indications of a systemic problem that can be addressed by local actions (e.g., personnel training) and globally for indications of population-wide problems which are best corrected by a design change or doctrine change.

An example of a global problem might be a batch of bearings that were of inferior quality but escaped detection until after installed. At the time the problem is discovered, it might be necessary to replace all the bearings in service. Without seamless capture of data during the repair process and a good logistics database, it would be impossible to identify this type of problem and very difficult to implement a repair without wholesale replacement of the suspect part.



Our activities in mechanical diagnostics and prognostics focus on only one part of the overall CBM process: Monitoring, Detection, Diagnosis, Prognosis, and the Decision to Act. These processes must occur serially in the order shown, though they may appear at times to be simultaneous.

The basis of this assertion is the hypothesis that all machines are progressing during their operation along several lifelines that will ultimately lead to failure. Until a fault initiates (probably at the microscopic level, and initially undetectable) there is no basis from which to predict the time to failure other than a statistical method based on a population of like machines. During that time, monitoring continues using all the capabilities available including human observation.

When a detection is made, i.e., an observable feature exceeds an acceptable threshold, the diagnosis process is started to determine the nature of the incipient fault. This step could be very simple based on the observed exceedence or it could require interrogation of the system or analysis of a combination of observable features.

Once the diagnosis is made, it is possible to start making predictions of the remaining useful life of the system. This process requires a prediction of the evolution of the fault in the context of future operational loads and will improve in precision and confidence as the machine continues to fail.

When the confidence is sufficient to warrant operator attention (with or without "man-in-the-loop" control) a decision support process is initiated. This process considers near-term employment schedules and resources available to affect the necessary repair. Both of these can alter a decision on when to take action. It is, of course, necessary to account for the decision to take no action and continue monitoring the evolution of the fault.

A Framework for CBM

- Offers a set of definitions - A "Glossary"
- Facilitates Communication of the concept
- Defines "How Well" We Need to Predict the Future to Make a Difference
- Prescribes the Research Agenda

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In order to undertake this research program, we had to develop a framework for communication among ourselves. The field has no established lexicon and, as a result, terms are used with different meanings. For example, a statement that this equipment is going to fail is sometimes called a prognosis or prediction. If that is truly a prognosis, I can be correct in 100% of my predictions - all machines will fail if operated long enough. The issue is knowing when the particular machine will fail, precisely enough and with sufficient confidence to warrant action by the equipment owner.

We've tried to clarify our communications by establishing definitions of the terms as we use them and to be consistent in our use of the terms. We feel it is important to do this to ensure that we accurately communicate our intentions and results.

This framework also allows us to define how well the technology must work to be useful in service. Without asking this question, the investment in research and development will without doubt be misapplied and successful implementation will be delayed.

Prognostics

The ability to reliably and accurately predict the *remaining useful life* of equipment in service.

- Required reliability and accuracy application dependent
- Prediction must have:
  - acceptable certainty
  - error bounds

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Prognostics is probably the most mis-used term in the area of condition-based maintenance. It is frequently determined by trending a particular (or combination of) parameter(s). The result is usually presented as a prediction that the machine will fail, presumably in the near future. Unfortunately, this is insufficient to warrant on the part of an owner (represented by an operator).

One must understand that remaining useful life is the important concept. Failure is too dependent on the application, e.g., a submarine bearing is failed if it is noisy, not so in a paper mill.

A prediction or prognosis must include error bounds around its expected value of prediction and must explicitly achieve an acceptable level of certainty.

Unfortunately for the researcher, these are decisions that must be make according to the application and by the owner. The researcher can only respond by developing technology that meets the requirement or identifying research needs in areas that require improvement to meet the requirement.

End of Useful Life

That point in the failure evolution of a machine
at which its owner would *choose not* to start
the next *mission*
if the true condition of the machine were known to her/him.

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In order to understand the concept of useful life, it is necessary to define the end of useful life.

It is important that this point in NOT failure in the normally understood sense of equipment being found unsuitable for the application during operation. It is rather a point where the machine is not predicted to continue satisfactory operation (defined by the owner) during the next (or an acceptable number of missions).

This is the point where the owner would not knowingly risk mission success on this equipment if he/she were able to accurately know the true condition of the machine.

Remaining Useful Life

- The operational time from the present until a system will not be able to successfully complete its next *"mission"* because it:
  - Won't be safe within acceptable confidence limits
  - Won't meet minimum tolerance levels
    - Noise (e.g., submarine bearings)
    - Dimensional accuracy of machined parts
    - Will operate below cost effective efficiency
    - Will fail catastrophically

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Remaining useful life is an operational time measure much more so than a calendar time. It is tied very closely with the concept of end of useful life where the owner would not knowingly undertake a mission because the required performance of the equipment will not be met and with an acceptable level of certainty, the equipment will jeopardize the mission's success.

It is important to note that there are any number of reasons a machine would not be able to successfully complete the next mission. It is not dependent only on a catastrophic failure, it could include a probability of failure that is unacceptable for the application based on objective evidence from the monitoring system.

Critical Prediction Horizon

- The time required by the operator to conveniently and/or safely take the required action for the particular failure trajectory.
- It is a function of:
  - Time between convenient repair opportunities (e.g. one mission)
  - The consequences of failure
  - The difficulty of the required action
- Defined as a constant times a number of repair opportunities

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Some points in the failure trajectory need to be established.

The critical prediction horizon is the point at which the owner defines he/she wished to be informed about an impending failure. It represents an integer number of missions that allow him to conveniently and safely plan and undertake the indicated action accounting for availability of resources, other influences like availability of back-up equipment, and lead-times for parts and scheduling.

Until the prognosis element predicts that the remaining useful life of the equipment is less than the number of missions required by the critical prediction horizon, the monitoring system will not inform the owner of the presence of an evolving fault, unless queried.

Critical Detection Horizon

- The time defined by the sum of the Critical Prediction Horizon and the time required to refine the projection of Remaining Useful Life to a sufficient confidence for the application.
- It is a function of:
  - Time to conduct analysis required to make prediction.
  - Consequences of a "Miss" and a "False Alarm"
- Defined as a constant times a number of Prediction Cycles

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Some points in the failure trajectory need to be established.

Critical detection horizon is much more applicable to the technology developer than to the owner. This time represents the amount of time required for the operator to take action(critical prediction horizon) and the amount of time it takes for the prognostic module to refine its prediction to an acceptable level of precision and confidence.

Prognosis will not likely be a one-time through process. It is expected to be iterative in nature, refining its estimate of remaining useful life after every iteration. It would be nice if the remaining useful life "clock" ran backwards at the same rate as the elapsed time on the equipment operations meter, but that is unlikely.

More likely, the system will make a prediction, monitor performance for a period of time, make another prediction, compare the results of the two predictions, and refine its prediction in an iterative process. As long as the time between detection and alert is sufficiently long to allow the prediction process to refine its prediction to an acceptable level, we can successfully implement CBM. If that time is not sufficient, we need to detect the incipient fault earlier or reduce the time our prediction requires to operate.

How Well Must We Do?

- Sensitivity Required for Detection is Defined by:
  - Time Required to Provide the Operator with Sufficient Warning (Critical Prediction Horizon):
  - Confidence in prediction high enough to warrant action
  - Enough repair opportunities to conveniently and safelytak action
  - Plus Time Required by the Analysis to Achieve the Necessary Level of Confidence in the Prediction
- Precision of Prediction Required is Defined by:
  - Risk (as Defined in Statistical Decision Theory) of False Alarm and/or Miss
  - Lower Risk Application Drives Higher Precision; Higher Risk, Lower Precision

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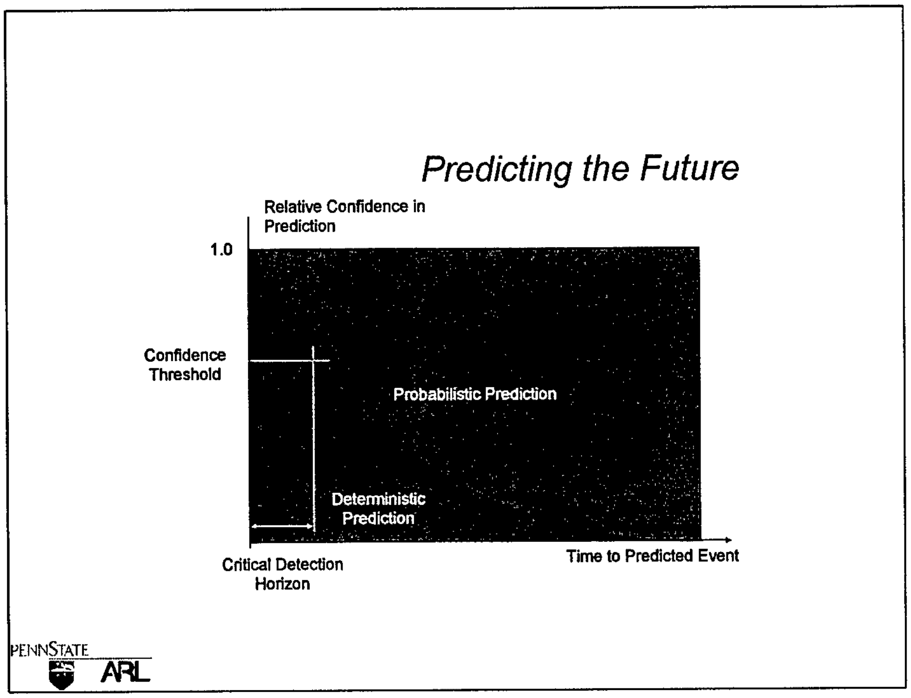
The definition of how well we must do comes from the owner of the equipment in question. It is important for us to understand this so that we can meet the requirements of the application. The system design should be such that adequate performance (that level that the owner is willing to pay for) is achieved, but the solution is not "gold-plated"

The above describe sensitivity and precision requirements to make a meaningful decision in the operational environment.



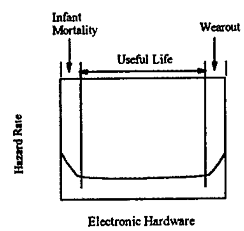
Predicting the future must rely on a probabilistic prediction based on a population of like machines when the time the predicted event (end of useful life) is long. The objective is to move to an increasingly deterministic prediction of remaining useful life based on monitoring of the individual piece of equipment and on developed models of the evolution of faults in the machine.

The user must place his confidence in one or the other of the prediction approaches. In a time-directed maintenance situation he is "by definition" depending on the probabilistic prediction based on a population of like machines. That is, because most (nearly all) of the machines in the population last for x-hundred hours and this machine has y-hundred hours (less than x), it is safe to undertake this next mission prior to a maintenance action.

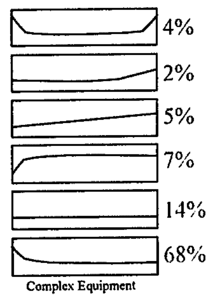
There comes a point in the evolution to end of useful life where properly constructed deterministic predictions based on monitoring of the individual machine and models of failure evolution reach a threshold of confidence where it is more prudent to trust that prediction over the probabilistic prediction.

Diagnostics and prognostics research must reach that level of confidence before the remaining useful life of the equipment is less than the "critical prediction horizon" or the time that the model requires to refine its prediction and the time that the owner needs to affect the required maintenance action.

Mechanical Failure is Distinctive



Source: Exhibit 2-13, Reliability Centered Maintenance, Nowlan and Heap



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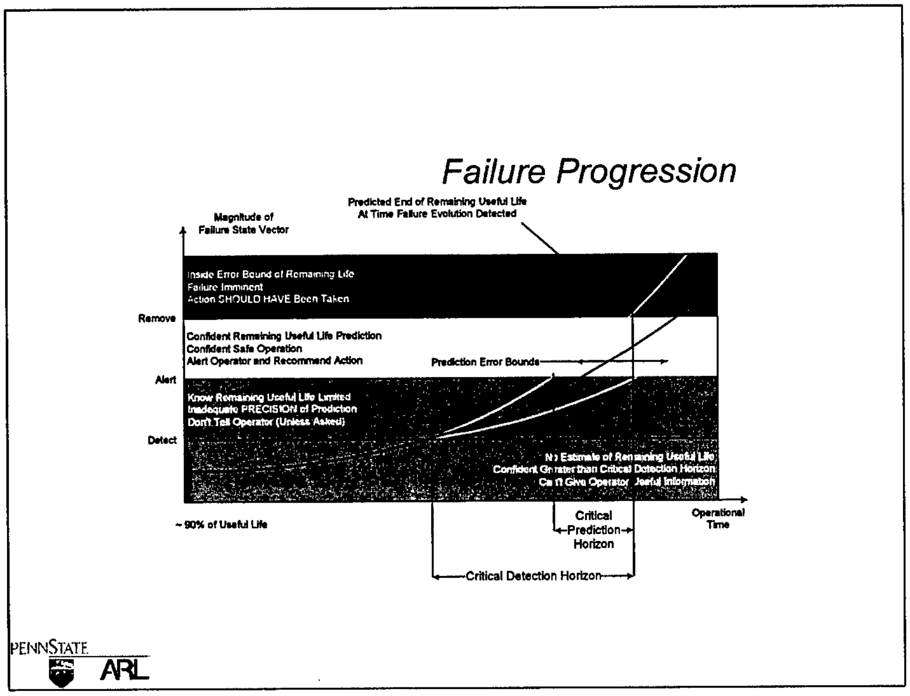
As a part of reliability-centered maintenance development, Nolan and Heap studied actual aircraft equipment to determine the observed hazard rate (probability of failure) as a function of operating time. Traditional reliability analysis depends on the concept of a "wearout" period as shown in the typical "bathtub curve" for electronic equipment. Unfortunately, mechanical equipment was not observed to behave so nicely.

Of the complex mechanical equipment items studied, only 11% exhibited a hazard rate curve in which a rational argument could be made for a time directed maintenance task. That is the time at which the hazard rate exceeds an acceptable limit. Those curves are the top three on the right.

The other 89% of the equipment exhibited a random failure (constant hazard rate) pattern at the time of maintenance or repair. For those equipment, there is no statistical basis for conducting maintenance at the applied periodic interval.

The bottom curve on the right shows the left side of the typical "bathtub curve". This may in fact be a true bathtub curve where the useful life of the equipment was truncated before reaching the wearout phase. The problem is that there is no way to know whether wearout would have started to occur (statistically) shortly after the maintenance action (in which case maintenance was conducted at the proper time) or if the wearout occurred much later (in which case useful machine life was discarded).



This generalized curve of machinery failure progression shows the evolution from the point where a "terminal" failure initiates (probably at the microscopic level at approximately 90% of life) to the end of useful life and beyond. The four zones represent increasingly accurate and precise predictions of remaining useful life.

In the first zone, the only tool available to predict remaining useful life is probabilistic based on a population of like machines. This encompasses most of the life of the equipment. Sometime after the fault initiates, it becomes observable using whatever surveillance methods are applied. At this point, the system "knows" that a fault is determining the remaining useful life and the probabilistic prediction based on a population of like machines is superceded by an analytical prediction. It will take some number of iterations of the analytical prediction process to refine the prediction and increase its certainty to a level appropriate to alert the operator. This occurs while the fault evolves through the second zone.

At the time that the confidence in the predicted remaining useful life reaches a level acceptable to the operator AND the remaining useful life reaches the "critical" prediction horizon", the operator is alerted. He then has the amount of operating time he specified to conduct the indicated maintenance action before the equipment progresses to the "remove" level of severity. Once the severity of the fault reaches the "remove" level threshold, failure can occur at any time.

Moubray's P-F Curve

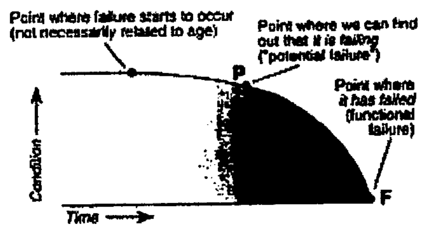


Figure 5.6:
The P-F curve

The P-F interval is the interval between the occurrence of a potential failure and its decay into a functional failure.

Moubray, John, *Reliabilitycentered Mainteance*, Industrial Press, Inc., 1992

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A generalized machinery failure evolution curve is presented in the RCM literature, this taken from Moubray.

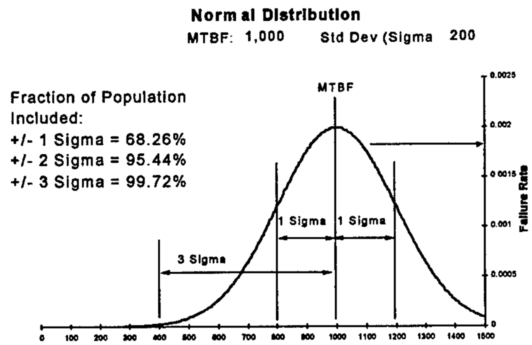
The vertical axis on this curve represents "health" and is the inverse of the vertical axis on the Penn State failure evolution curve which represents damage.

Important points to note on this curve are that the point at which failure starts to occur may or may not be related to age. There is a point where the fault is detectable and there is a point at which the equipment has reached "functional failure". In the RCM vernacular, functional failure is analogous to our "end of useful life"

A significant difference between this curve and the curve presented by Penn State is the lack of the intermediate alert point. Depending on one's point of view, the alert point from Penn State's curve falls either on point "P" or between point "P" and "F".

I contend that establishing a separate threshold after detection, but before functional failure, is an important addition to the RCM perspective. This point is intended to account for the fact that an operator will have a number of equipments, all of which are at some point in their evolution to failure and triage is imperative. Providing information prior to the time at which it is necessary for him to act interferes with his ability to operate the fleet or enterprise.

A Simple Failure Distribution



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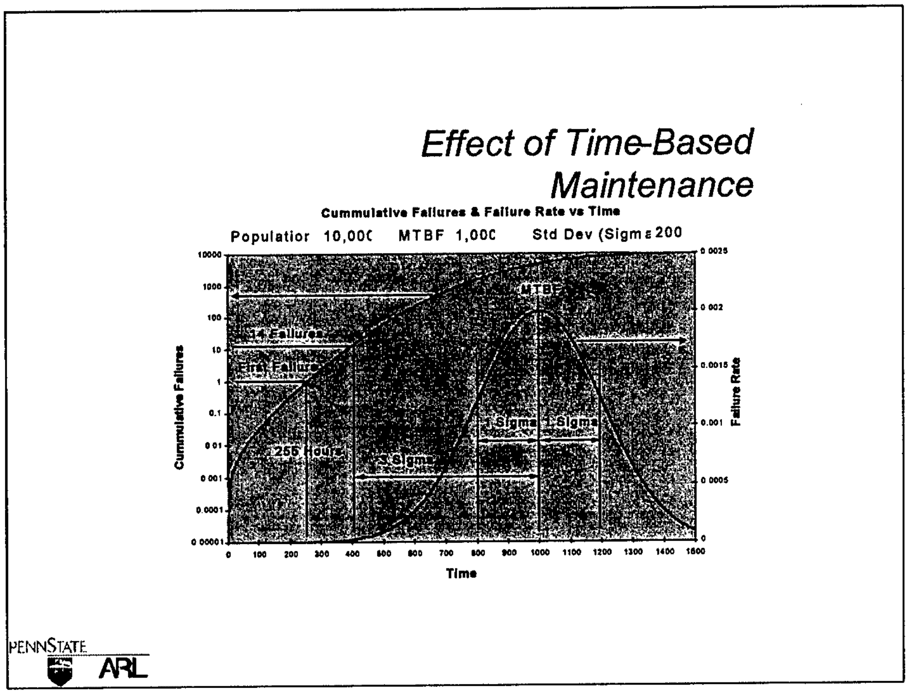
A little description of statistics and what they mean in a planned, time-directed maintenance philosophy.

The simple failure distribution shown above is the normal distribution. It is chosen because it is the easiest to work with and most familiar to most readers, but also because it fairly represents a wearout failure process for a population of equipment.

Above is shown the normal distribution assumed based on an analysis of a large population of machines over a period of time. It is not meant to be a projection of life, but rather a representation of experience in the population. The mean of the population is observed to be 1,000 with a standard deviation of 200. The mathematics of the normal distribution the define that the percentages of the populations shown will be contained within the lifetime of + or - 1,2, or 3 standard deviations or sigma.

As you can see, the failures that occur prior to three standard deviations (3-sigma) before the mean will be 0.14% (1/2 of those not contained within +/- 3 sigma. That seems like a very small number and might represent a good place to establish a maintenance level for this equipment item.

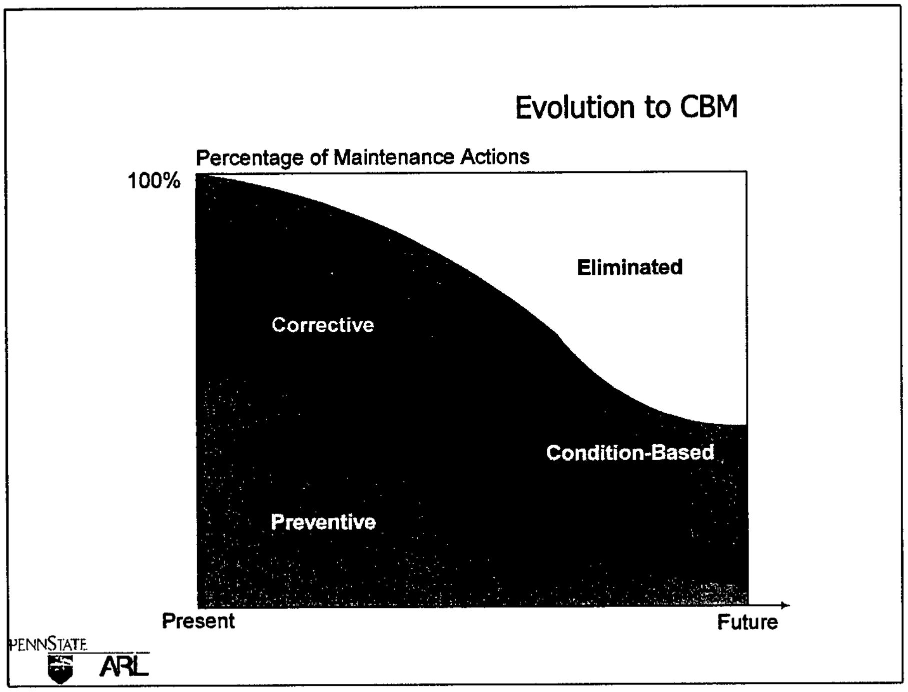


Above is the normal distribution presented elsewhere with cumulative failures plotted for a population of 10,000 items. While this may be a large number for the types of equipment usually considered, it is chosen to make the numbers work in integers rather than fractions. The impact on the enterprise is the same whether we talk about a population of 100, 1,000, or 10,000.

As can be seen, the first failure in this population of 10,000 will occur statistically after only 255 hours of operation. The problem is that the statistical prediction will tell you absolutely nothing about which of the 10,000 units that will be.

If this were a critical item, the maintenance interval might be set a 3-sigma below the mean. Setting the maintenance interval at that point implies that the owner is willing to accept 14 failures in the population of 10,000 and that he is willing to "throw-away" useful life (in 5,000, those that lie on the right side of the mean, more than 600 hours) on 9, 986 of the items.

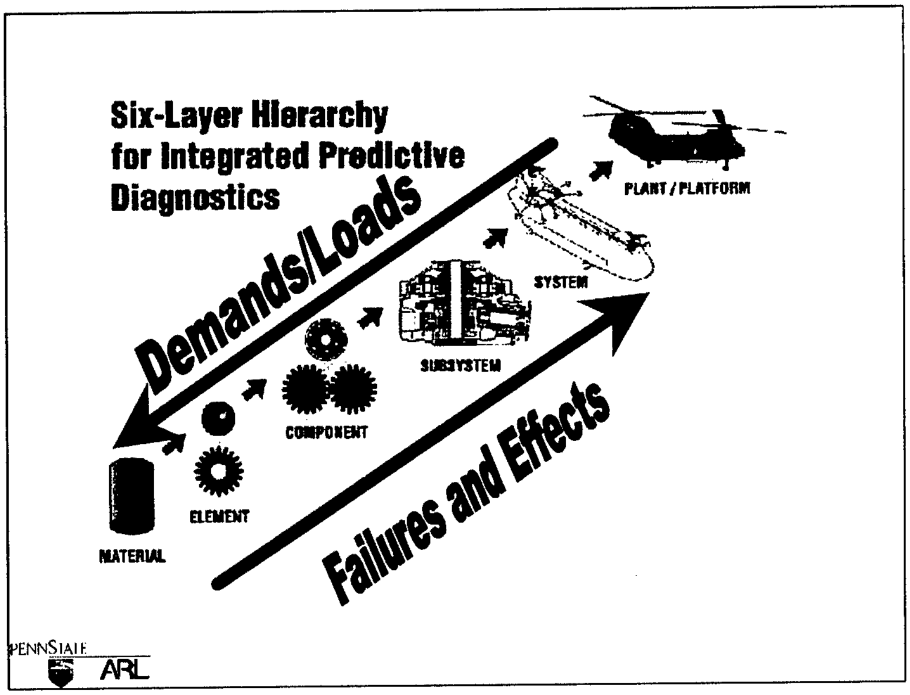
This may be an acceptable trade-off in some applications, but it highlights a great opportunity for monitoring on an individual equipment basis and analysis of the health of the equipment if it can be performed cost effectively and reliably.



The evolution to a more efficient and effective maintenance philosophy will occur over time and will always consist of some mix of condition-directed, corrective, and time directed maintenance actions.

The current state in the military is that we perform a large amount of preventive maintenance, a large amount of corrective maintenance, and some condition-directed maintenance. The objective is to eliminate unnecessary maintenance actions, conduct most maintenance on-condition when the particular unit requires it, conduct some corrective maintenance because the monitoring systems will never be perfect and it will always make sense to operate some equipment in a "run-to-failure" mode (e.g., room lighting), and maintain some equipment solely on time.

Those items which would remain in a time-directed maintenance mode would be those with moderate level of consequences of failure (too much to allow to run-to-fail) and a very tight failure distribution around a mean. For example, if you consider a normal distribution with a mean of 1,000 and a standard deviation of 10, this might make a good candidate for time directed maintenance. If the population exhibited a mean of 1,000 and a standard deviation of 300, it probably would not be a candidate for time-directed maintenance actions.



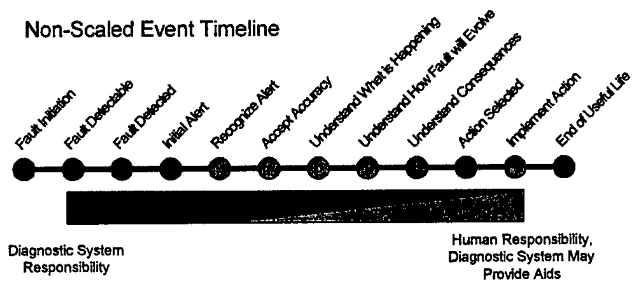
In order to organize our research in a manner that allows results to be applied to a variety of equipment, we needed to establish a hierarchy of a plant or platform. This enables us to understand failure and the observables of failure in materials and to translate them into a variety of applications. The generalization comes from the fact that mechanical systems and subsystems comprise standard components including gear meshes and bearings. If we can monitor and understand failure progression as a function of load in these components, we can translate that up to the plant or platform level.

The basis of this approach is that all demands and loads on the system come from the plant or platform which is the point at which an asset is assigned a definable mission, e.g., carry troops across the beach. This mission is the driving factor and all elements of the plant or platform are consumables that must be managed in accomplishing the mission.

Failure does not start until the ability of the material to carry the load demanded of it from the plant or platform exceeds its strength. Certainly environmental factors impact the strength of the material, but failure does not occur until the load imposed exceeds the environmentally reduced strength of the material.

Effects of these material failures progress back up the hierarchy to effect the mission of the plant or platform. It is not until the mission is effected that the operator should be concerned other that managing consumption of the equipment.

Allocation of Responsibility



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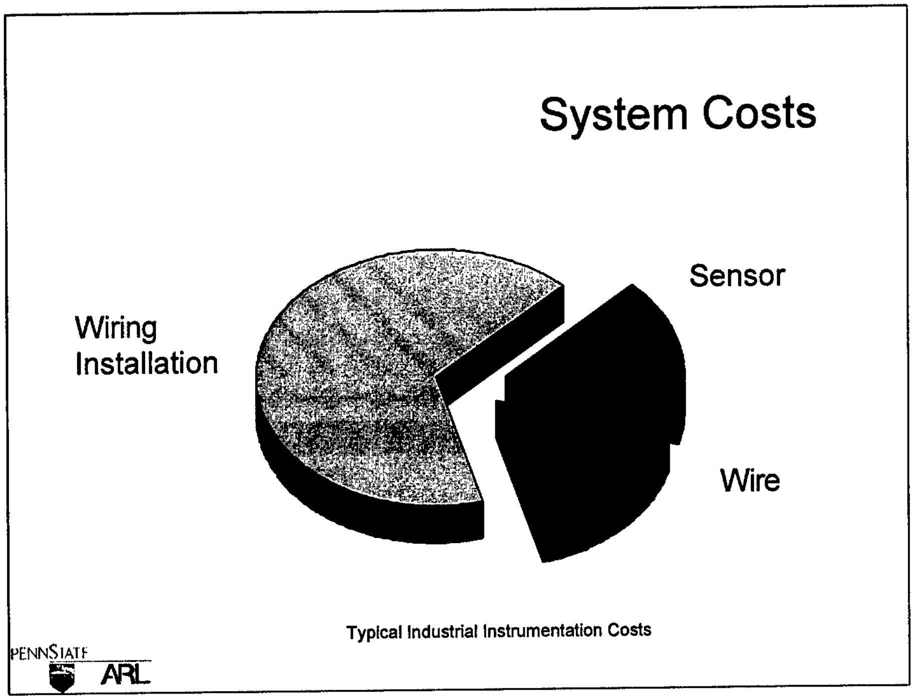
Since we are attempting to automate or at least support the human decision process in operational equipment, it is important to consider where the computer's responsibility ends and the human takes over responsibility.

The above represents a continuum in the decision process that must be traversed prior to an action being taken. Each of the steps are accomplished in series from left to right. In experts, they may appear to be accomplished in one leap, but that is because training and experience have "hard-wired" the response based on inputs. In development of the training process, then, each of these steps must have been considered.

Each application will be amenable to allocating greater or lesser responsibility to the computer. Previously, humans have been very reluctant to give up authority to the computer in any but those cases where the time-frame of response was too fast for the human to manage, e.g., fighter aircraft flight controls.

In the current fiscal constrained environment, however, greater emphasis is placed on designing the human out of the loop and enabling more autonomous action by the system.

Wherever a particular application lies on this continuum of responsibility, it is imperative that the systems and technologies developed accommodate human intervention wherever the owner desires.



In determining how we should approach implementation of advanced monitoring technologies for diagnostics and prognostics, we investigated where the costs go in installing on-line monitoring systems. We found that typically 60% of the cost is installation of wiring.

Further, the most vulnerable and unreliable portion of the system is the wiring. It is prone to be cut or break along its length and problems with connectors are the bane of any monitoring system.

We have chosen to attack this problem by developing a wireless approach to information collection. This entails a hierarchical design where monitoring and analysis are conducted at low levels in the mechanical system hierarchy presented elsewhere. Pushing the processing out to the component level has two positive effects.

First, it allows generic developments that can apply to a large variety of applications. It is inherently object-oriented and associates processing with a tractable portion of the system, i.e., predicting the life of a bearing is easier than predicting the life of a transmission made up of multiple bearings and gears.

Second, it dramatically reduces the transmission bandwidth required for communication. This distributed processing reduces the data flow from an accelerometer measuring 20 kHz vibration at 24 bits resolution for a total bandwidth of 480,000 bits per second data stream to an information stream of a few bytes on demand or periodically stating the current health of the monitored bearing.

Why Wireless?

- Typical Helicopter HUMS Installation: 35 to 40 Sensors
- Projected Cost Reduction using Wireless

– Sensors	$0	Sensors Same Cost
– Sensor Installation	$0	Equivalent Installation
– Wiring Installation	$70,000	35 Sensors @ $2,000
– Wiring Cost	$17,500	35 Sensors @ $500

- Savings/Aircraft $87,500

MAWCAD, PAX, Phase II SBIR, Invocon, Inc.

Topic: Wireless Airborne Instrumentation System

Reduce Wiring Time for High Performance Aircraft Flight Testing from 9 Months to 1 Month

Scheduled Complete Early CY 98

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Wires are the most expensive, least reliable, and most vulnerable portion of the monitoring system. This provides an example of potential economic benefit of applying wireless sensing in an airborne application - helicopter health and usage monitoring systems.

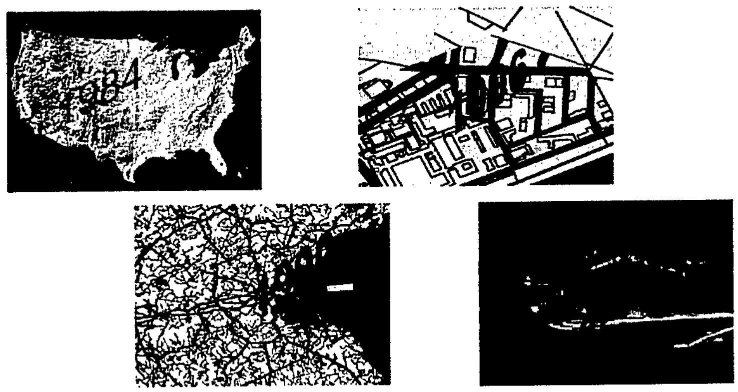
The analysis presumes a typical HUMS installation will comprise around 35 or 40 sensors. Breaking the installed cost of the sensors and wiring into four categories the savings a wireless installation offers over a conventional wired installation is shown.

Sensors and sensor installation are shown at the same cost for either option. This is a design goal to make our wireless sensors form and fit compatible and cost competitive with conventional wired machinery monitoring accelerometers.

Sensor wiring installation is the largest saving. At a conservative cost estimate of $2,000 labor (fully burdened, including QA, etc.) per channel and assuming 35 sensors per aircraft, savings of $70,000 per shipset are projected. Additional savings of $500 per channel for sensor wiring translate to $17,500 per shipset for a total of $87,500 or approximately 1/3 the total installed cost of the system.

Technology to enable wireless transmission of data in an aircraft environment is being adapted from an SBIR for high-performance aircraft flight testing wireless data acquisition by Invocon, Inc. The technology is a dynamically reconfigurable wireless array of sensors.

10,000 Network Connections



Source: MIT Media Lab
http://www.media.mit.edu/pia/Pubs/TTT_9610

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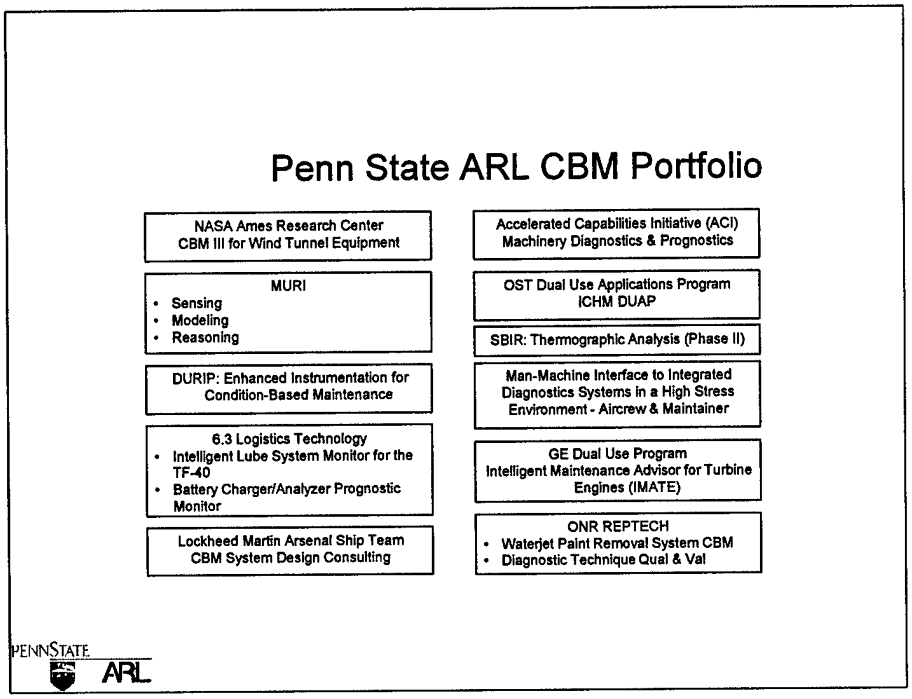
There are a number of technologies advancing at an unprecedented rate, one of them being the internet.

Above shows the growth of internet connections in the US over an 18 year period.

In 1984 there were 10,000 network connections in the continental United States. Six years later, that same number of connections were established in the Boston Metropolitan area. Six years later the MIT campus had 10,000 network connections and in 2002, one building, the Media Lab building, is expected to have 10,000 connections.

While the availability of network connections is important, it is less that than the industry and technology base that has grown to support this explosion. We should be directing our efforts toward approaches consistent wherever possible with the internet. Using internet protocols, using software developed for the internet, and applying standards as they evolve. A commercial internet capable of supporting e-mail and web-browsing will not by itself solve our problems, but the tools that evolve to support the internet should certainly help us.



Penn State ARL has assembled a broad portfolio of projects in Condition-Based Maintenance. The projects range from basic research in the MURI to very applied, particularly in the work on NASA wind-tunnel support equipment. Other projects span the range from research to application according to the particular sponsor and application requirements.

REPTECH Diagnostic Technique Qualification & Validation

SOLUTION

- Collect believed good data on a full squadron of H-46 aircraft (10 aircraft)
- Archive data, make available via Intranet for rapid analysis
- Conduct Measures of Effectiveness/Measures of Performance on all Analyses Conducted

BENEFITS

- Reduced false alarm rate at implementation of Health and Usage Monitoring Systems (HUMS)
- Dress rehearsal of squadron level response to HUMS alerts

OBJECTIVE

Develop and validate a procedure that will qualify diagnostic techniques for mechanical equipment to avoid potential for excessive false alarms as HUMS enter fleet.

RELATED EFFORTS

- ONR Condition-Based Maintenance Advanced Capabilities Initiative: Development of advanced diagnostic technologies
- Integrated Mechanical Diagnostics implementation roadmap
- Advanced Maintenance Environment (AME)

IMPLEMENTATION

- Develop and demonstrate means and metrics to independently qualify alternative diagnostic technologies
- Transfer capability to program offices and depots for use in acquisition selection

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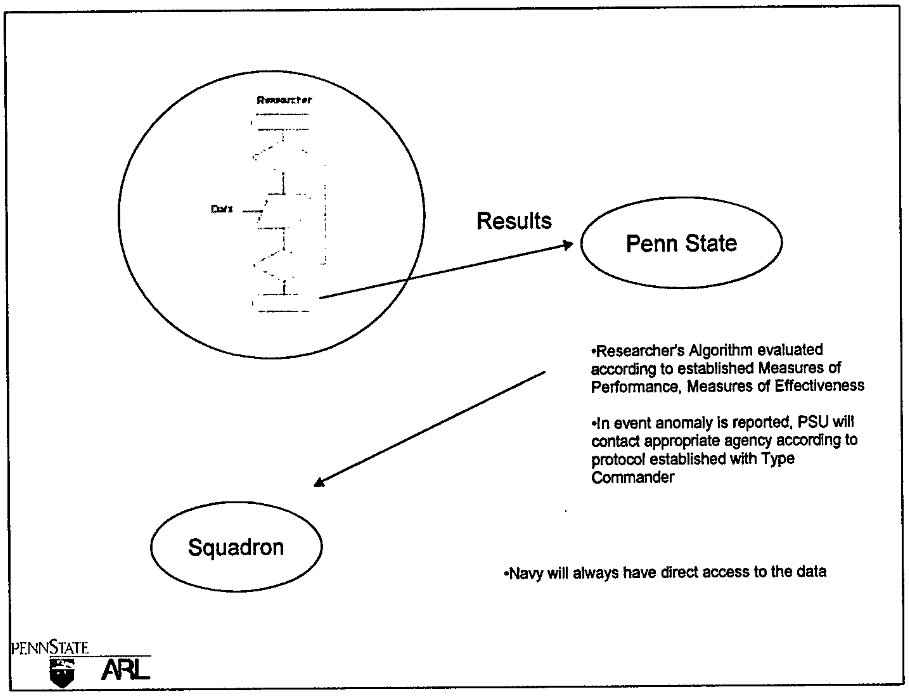
One of the key limiting factors in development of reliable diagnostic and prognostic technologies is lack of high-fidelity data correlated with actual fault conditions in equipment. A limiting factor in application is a lack of reliable measures of performance and effectiveness for the techniques. This project begins to address both concerns.

The intent is to collect a large database of high-fidelity vibration data on a fleet of active aircraft. This data will be directly correlated with previous seeded fault test-stand data collected by the US Navy. The datasets collected will be made available in near-real-time via an intranet to a variety of researchers each of whom will analyze the data and report results to the Penn State repository.

Additionally, the monitored components of the aircraft (aft main transmission) will be tracked to the repair facility. When a transmission that is in the monitoring program is removed from service for either cause or time, its condition will be assessed at the depot. These "ground truth" results will also become part of the repository at Penn State.

These results will be compared against a set of measures of effectiveness and measures of performance that are currently under development in another project. This will enable the evolution of an unbiased measure of how well a particular application as well as a measure of the cost of implementing the technique in terms of sensor fidelity, processing requirements, monitoring time, etc.

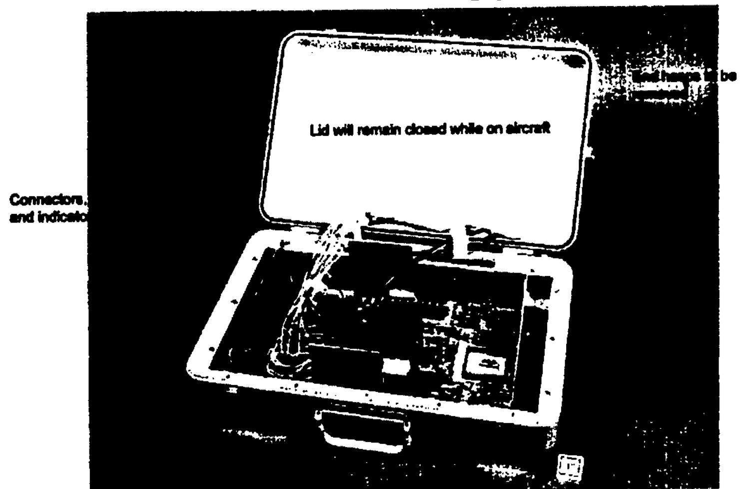


This project entails a high degree of interaction between researchers, Penn State ARL, and the squadron. Researchers have agreed to analyze data from individual flights within seven days of receiving notification of its availability. The results of these analyses must then be reported to Penn State ARL along with performance metrics relating to computing load and data quality required. These results and metrics will be compared among researchers by data set and over all data sets.

In the event an anomaly is discovered by any of the researchers, Penn State will contact the Type Commander in accordance with an established protocol to determine the response at the squadron level. These analyses are treated as additional information, all maintenance decisions in the squadron remain based on OPNAVINST 4790 and the Naval Aviation Maintenance Plan.

Owing to the Navy's investment in the data and infrastructure, access to both data and the results of the analysis by individual researchers will be assured for the Navy. Limitations on distribution of data and/or results of analyses will be determined as part of the agreement providing access to the data.

Information Logger in Chassis



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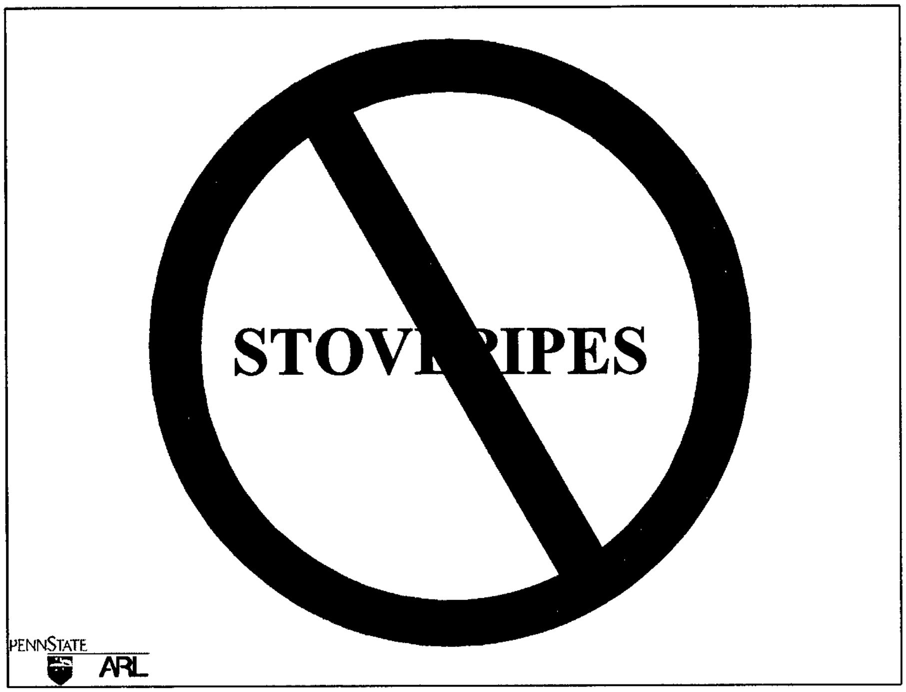
Key to building a successful and useful data archive is populating it with archival quality data. Bandwidth, dynamic range, and all signal conditioning/pre-processing done to the data must be clearly documented and sufficient for most of the research community.

Key to being able to collect data in an operational fleet environment without on-site technical personnel is a device and process that minimally interferes with the performance of the mission and does not place an undue burden on the squadron. The information logger shown is designed with both of these requirements in mind.

The technical specifications on the recorded signatures were reviewed by several members of the diagnostic development community. While each reviewer had specific requirements, some of which were conflicting, the box was designed to be a reasonable compromise that could collect the best possible data within the operational constraints of fleet operations. The box stores all information digitally and is designed for post-flight download directly to a web-server for dissemination. Detailed technical specifications provided elsewhere.

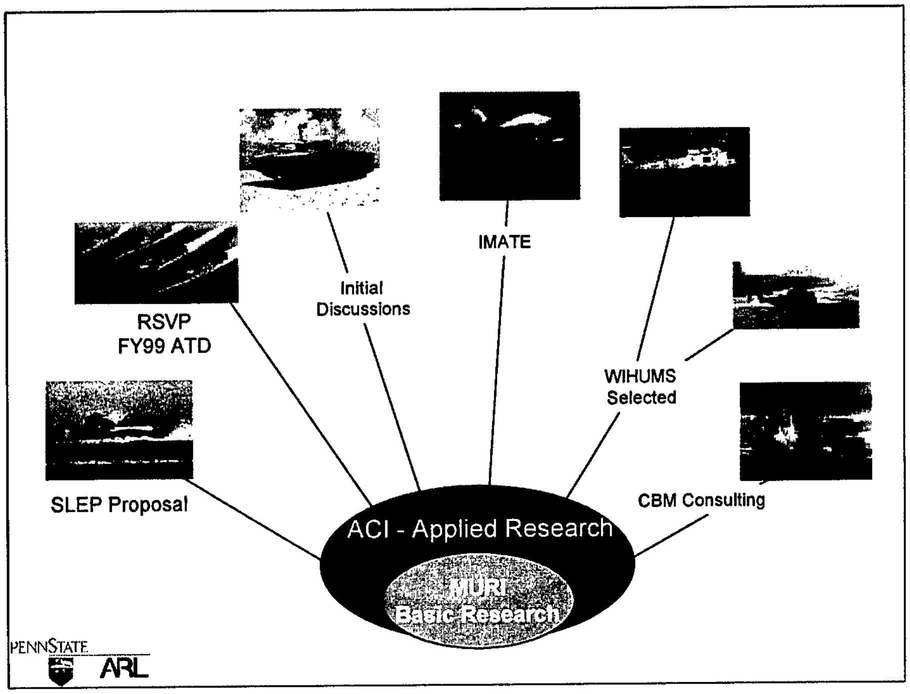
The information logger must also meet flight safety requirements and be operable by the crew-chief without an undue burden. The box was designed for and met flight clearance requirements with interim clearance granted 3 Oct 97. From an operational standpoint, the crew straps the logger into the aircraft, connects 1 plug to power and a second to data, flips one switch, and goes flying.



A fundamental precept of our approach to this technology is that single-point solutions are unacceptable. Every design and development must be developed with a broad range of applications in mind. While this may require some performance or cost compromises in some applications in the near term, the ability to use the technology across a broad range of applications results in a market volume that enables order-of-magnitude cost reductions. If the technology is redeveloped for every application separately, non-recurring engineering costs as well as costs of building installed hardware will be too large to justify the investment.

A specific and apropos example is the need for commonality between commercial and military instantiations of the equipment. Our approach favors distributed, highly-autonomous, devices monitoring and determining the health of the components. This requires that there be many of these devices per platform. In order to be affordable, they must be made in large quantity. In order to reach large production quantities (millions per year) they must be common in large part across a multitude of applications. Thus a bearing monitor in a paper mill should vary minimally from a bearing monitor on a helicopter tailrotor driveshaft.

The phrase I like to use is “commercially viable meeting military requirements.” This is achievable if the military uses its leverage in the research budgets to develop technologies that can meet this objective.



We are working very hard to ensure that the results of our research do not die in the laboratory. All acquisition and development programs for the foreseeable future will be striving to realize the benefits of condition-based maintenance as we describe it.

On the military side, we are trying to coordinate our developments to fill needs with major acquisition programs. As shown above, we have been successful in becoming directly involved in many. These efforts will continue.

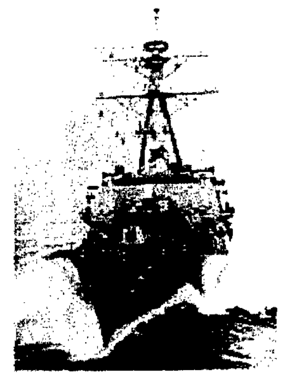
The issue in transitioning technology is timing the research program such that it reduces risk to the appropriate level for the acquisition program manager to be able to assume the risk in a program. It is inappropriate to expect the program manager to assume technical, program, schedule, or cost risk to incorporate unproven technology. The problem is that it is difficult to carry a development program far enough along to reduce the risk to that level without the direct support of the program manager.

The research community is frequently asked the question "What have you done for us lately?" The answer is ALL the new technology that is being applied in this acquisition. The problem is that the time between technology maturation and insertion is so long that the tie back to the original research and development effort is often lost.

Integrated product teams and similar initiatives are attempts to shorten the time and improve linkage between development and application.

Demonstration Target

Allison 501-K34
Ship Service Gas Turbine Generator



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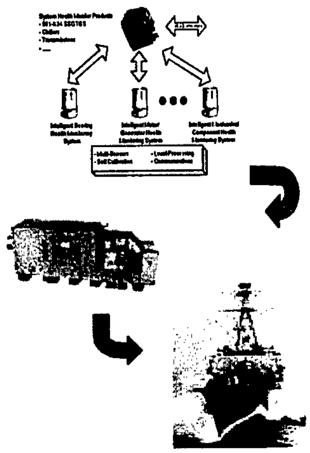
In the Office of Naval Research Future Naval Capabilities Option (FNCO) program we were fortunate to receive an award in the mechanical diagnostics and prognostics program. The demonstration vehicle for the technology developed was chosen by the proposing team as the Allison 501-K34 (AGT-9140) Ship Service Gas Turbine Generator Set in the DDG-51 class. Generally, the scope of the project is the equipment contained on the skid shown.

The Allison GenSet was chosen after Allison Engine Company was selected as a team member. Involvement of the original equipment manufacturer (OEM) is considered by us to be critical to the success and ultimate transition of this technology. Rather than pick the application and try to recruit the OEM, we began a dialogue with Allison and selected the 501-K34 as the item of their equipment providing the best demonstration vehicle for our technology considering the scope of the effort, available data and test resources, and the guidelines of the opportunity.

It is important to note that it is not the intention of this project to develop a complete health monitoring system for the 501-K34. Rather, we are using the 501-K34 as the equipment on which we demonstrate technology being developed for a wide variety of applications. Thus we may develop and implement some technologies not totally driven by the requirements of the genset and we may not undertake other challenges that might be of interest to the application but are outside the scope of this project.



Technical Goals

- Develop a multi-layer hierarchical architecture and implement machinery health monitoring at component, machine, and system levels.
- Demonstrate on Allison 501-K34 SSGTG
- Develop commercially viable products meeting US Navy requirements
- Produce commercial Intelligent Bearing Health Monitor Product (private funds)

PENNSTATE ARL

Our proposal outlined the goals of our project as above. The first is the primary goal of our effort.

We intend to develop and demonstrate an architecture, hardware, and software that enables cost effective machinery health monitoring and ultimately prognostics by distributing processing to the component, machine, and system levels. The details of the logic of this approach are described elsewhere but it entails using mainstream technologies where possible (like PC-104 and Compact PCI) to leverage production and development tools.

The demonstration vehicle for our technologywil be the Allison 501-K34 SSGTG(AGT-9140) working in cooperation with the OEM, Allison Engine Company.

A key driver for our development is commercially viable products that meet US Navy needs. This provides great leverage on the USN research funding to place items “on the shelf” for later removal as “COTS” that fit precise navy requirements.

The first such item planned is an Intelligent Bearing Health Monitor that will be commercialized by Oceana Sensor Technologies, Inc. We are confident that a near-term product will be a viable commercial product without reaching all of our cost, size, and weight objectives which become more important on high performance military platforms.

Team Members

The team we assembled for this project is well-suited for our approach and provides all the necessary elements for success.

In the upper right corner is shown NSWCCD. They are the in-service engineering agent for the 501-K34 and represent the end user.

In the opposite corner is Allison Engine Company, the OEM for the 501-K34. Their involvement provides access to detailed technical information on the system and a vehicle for implementation in both commercial and military applications.

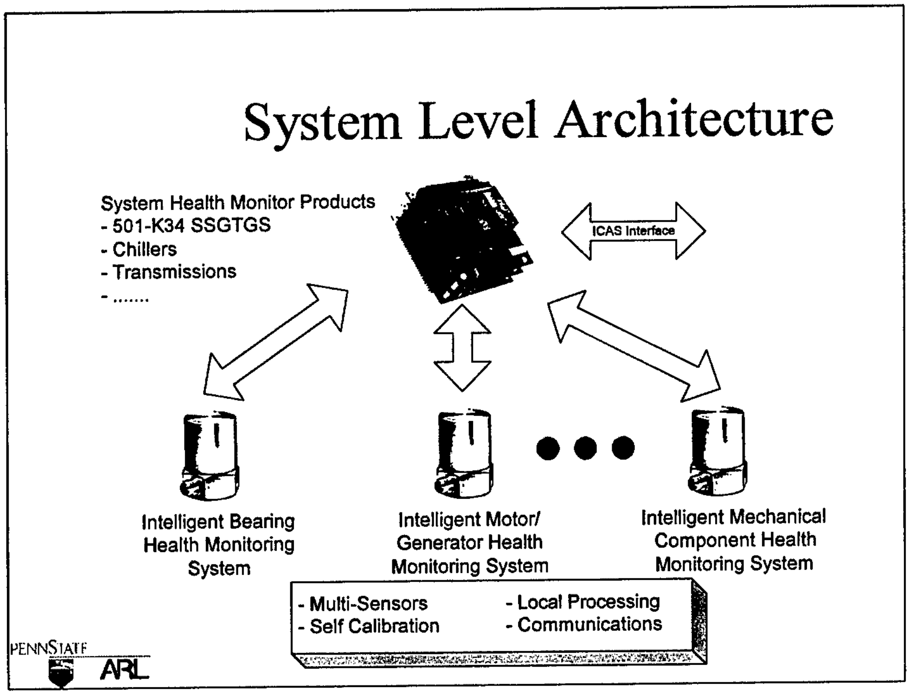
Oceana Sensor Technologies is a small company specializing in large-scale, low-cost production of high fidelity, smart sensing elements primarily based on piezo technology. They will commercialize the ICHM products.

Invocon brings a dynamically reconfigurable wireless array technology that supports high reliability wireless communication in a noisy and variable electro-magnetic environment using low-cost, low-power radios.

Timken, while not a part of the current project represents an insertion opportunity at the component level, i.e., embedding the technology in a bearing.

Newport News Shipbuilding is also not specifically involved in the current project but offers an insertion opportunity at the other end of the spectrum.

Others represent technology developers with specific strengths. Together we cover the range of capabilities required to ensure success.


System Level Architecture
System Health Monitor Products
- 501-K34 SSGTGS
- Chillers
- Transmissions
- ....
ICAS Interface
Intelligent Bearing Health Monitoring System
Intelligent Motor/ Generator Health Monitoring System
Intelligent Mechanical Component Health Monitoring System
- Multi-Sensors
- Self Calibration
- Local Processing
- Communications
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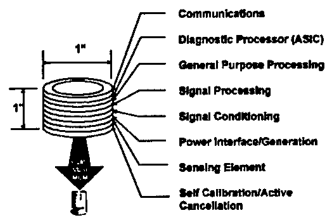
Product Description

Intelligent Component Health Monitor



- Integrated multi-parameter sensing and processing - produces component health assessment vice data
- Reliable wireless communications
- Accommodate self calibration and active noise canceling
- Define and consolidate functions to produce ASIC fcr large quantity production

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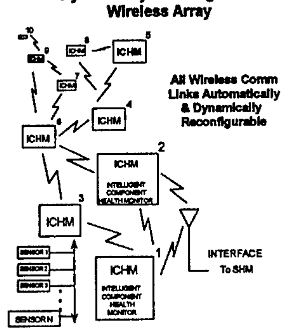
Product Description

Dynamically Reconfigurable Wireless Array



- Local "Sensor Fusion" Processing
- Maximize Advantage of Evolving MEMS Radio Technology
  - Operate on Low Power
  - Small Size and Weight
- Communicate on High Speed Wireless Links
- No Interference with Vehicle Navigation, Communication, or Flight Control
- Automatically Form a Network
  - Learn Optimal Network Configuration
  - Route Data via Redundant Paths
  - Collect, Store, and Transmit Data to One or More SHMs

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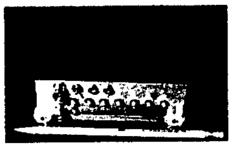
Planned ICHM Evolution



Starting Point

- Wireless Reconfigurable Network Comm
- Multi-Channel Data Coll
- Collects from COTS Sensors
- Interface to PC DAQ

ACI IBHM

- 1 in^3, $500, Conventional Pkg
- Wireless Reconfigurable Network Comm
- Integrated Multi-Sensors
- Integrated DSP/Analysis
- Interface to SHM System

MURI/ACI Goal

- Fully Integrated Chip Solution, $50
- Wireless Reconfigurable Network Comm
- Integrated Sensors, Power Scavenging, Processing
- Self Calibrating, Noise Cancelling

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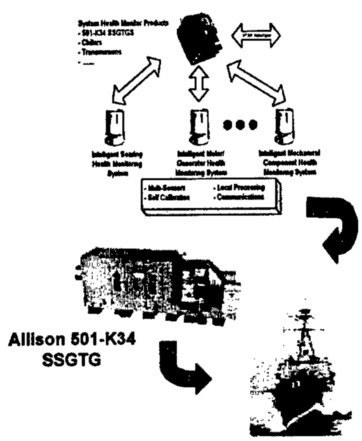
The technologies employed in these systems are evolving rapidly owing to their widespread use in commercial applications. The building blocks of our system will continue to get smaller and cheaper whether or not we are in the market place. Our goals are to rapidly take a current product providing wireless data transmission in a high noise environment, adapt that device for our use by putting additional intelligence in the node, and reduce the size of it through increasing levels of electronics integration to make it form and fit compatible with existing sensors in the market place,

When ongoing efforts at MEMS device yield usable results, more and more functions will be resident on a single piece of silicon (or whatever semiconductor substrate one chooses) to enable introduction of a single-chip ICHM. When we achieve that, we can truly say we have achieved the goal of a diagnostic system on a chip.



Summary

Program Objectives

- Develop a multi-layer hierarchical architecture and implement machinery health monitoring at component, machine, and system levels.

System Features

- Reliable wireless communication
- OEM integrated
- Open architecture - HW & SW
- Large production quantities

Milestones

- Breadboard ICHM Apr 98
- Breadboard SHM Apr 98
- Brassboard M/GHM Jan 99
- Brassboard ICHM Apr 99
- Brassboard HMS Jun 99
- Land-Based Testing TBD

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The FNCO in Mechanical Diagnostics and Prognostics at Penn State ARL is developing the hardware and software to demonstrate a multi-layer, hierarchical machinery health monitoring system. The system will feature reliable wireless communication suitable for shipboard use, integration into a demonstration piece of equipment by the OEM, an inherently open architecture for both hardware and software, and devices that are produced in large quantities for applications in both military and commercial systems. This meets the objective of a commercially viable product meeting US Navy requirements to make the results cost effective for Navy application.

The milestones shown are probably optimistic at this writing in February 1998. Funding for the program in FY97 and FY98 was not at the level originally planned. Expectations are that the program will be fully funded but at a slower rate. The program will proceed at a rate consistent with funding provided by the Navy.

APPENDIX C

Reliability-Centered Maintenance Analysis

Presented by: Les Johnson

25-26 September 1997

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Reliability-Centered Maintenance

RCM Overview

- What is RCM?

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Background

RCM History[1]:

- started in DoD and Civil Aerospace (United Airlines)
  - evolved from maintenance steering group (MSG-1,-2,-3)
- improvement or traditional "scheduled overhaul" method

[1] Per Moubray, *Reliability-Centered Maintenance* 1992

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RCM Analysis

RCM determines:

- functions of systems,
- possible failures of those systems,
- modes of failure,
- effects of failure,
- consequences of those failures.

RCM Analysis

RCM recognizes:

- scheduled on-condition tasks,
- scheduled restoration tasks,
- scheduled discard tasks,
- default tasks.

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Failure Analysis

Some common root causes of failure:

- dirt,
- inadequate lubrication,
- disassembly (or misassembly),
- incorrect set-up or operation,
- incorrect process or packaging materials.

Device Monitoring

Methods to prevent or reduce failure(s):

- protective devices,
- fail-safe (if monitoring device fails, notice to crew is given),
- condition monitoring.

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Condition Monitoring

- Dynamic effects (vibration, acoustic emission),
- Particle effects (discrete sizes),
- Chemical effects (traceable quantities),
- Physical effects (cracks, fractures, wear),
- Temperature effects (changes),
- Electrical effects (conductivity, dielectric strength),
- Leaks (pressure, flow).

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RCM Benefits

- Enhanced understanding of equipment operations,
- Better understanding of failures and root causes,
- Proposed tasks to maintain operation,
- Improved operating output,
- Lower costs,
- Improved teamwork and motivation of personnel.

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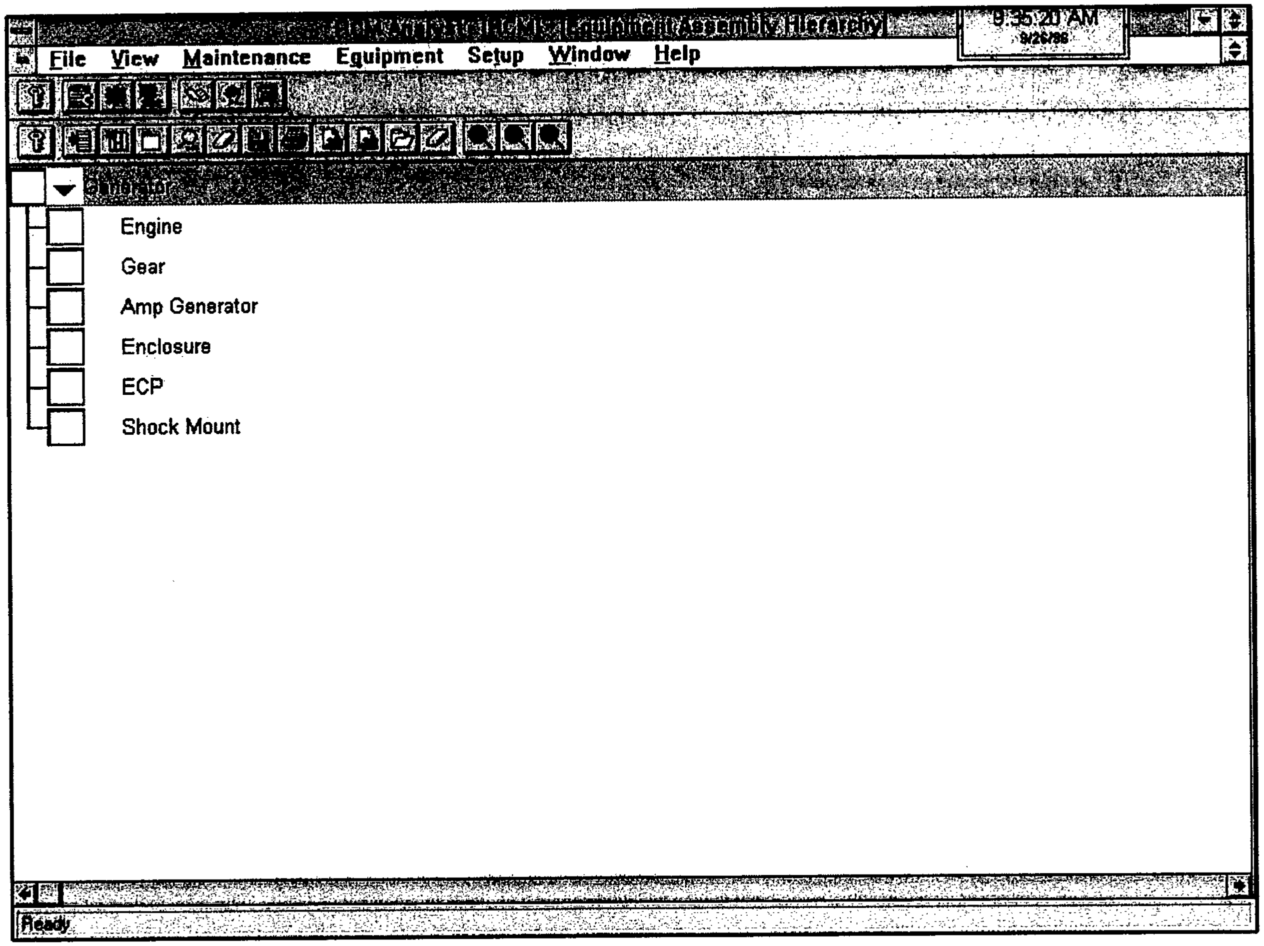
Equipment Assembly Hierarchy



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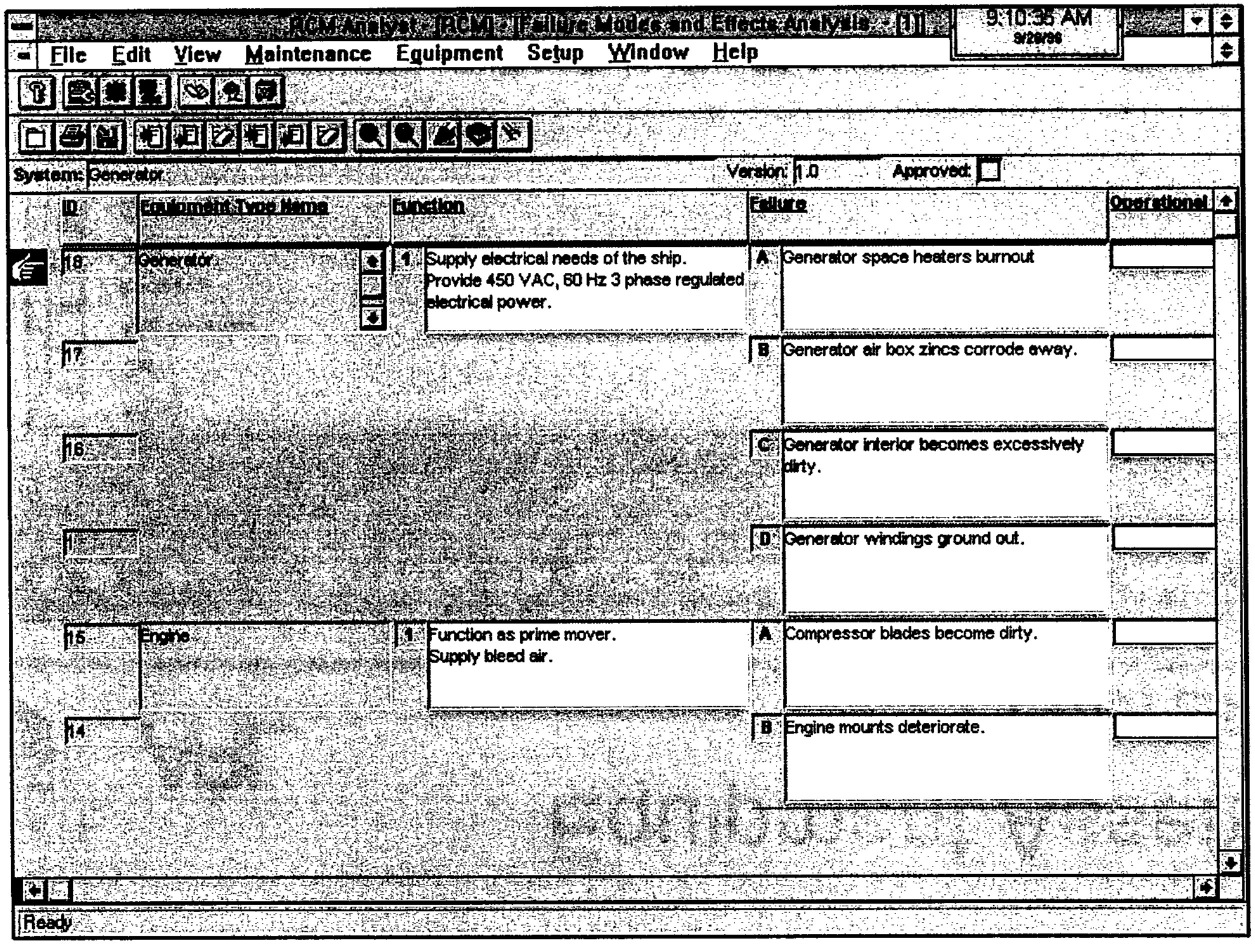
Failure Modes and Effects Analysis



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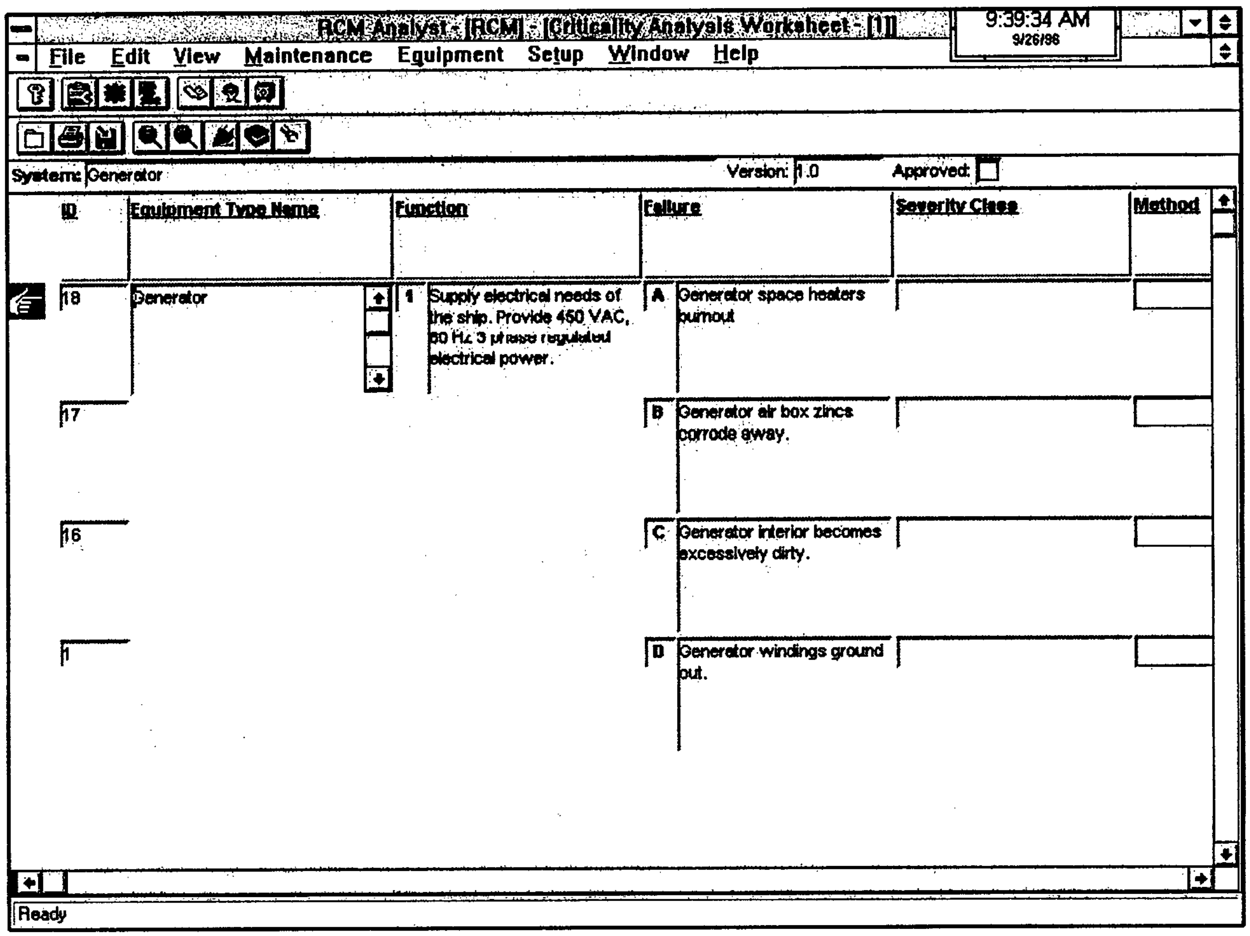
Criticality Analysis Worksheet



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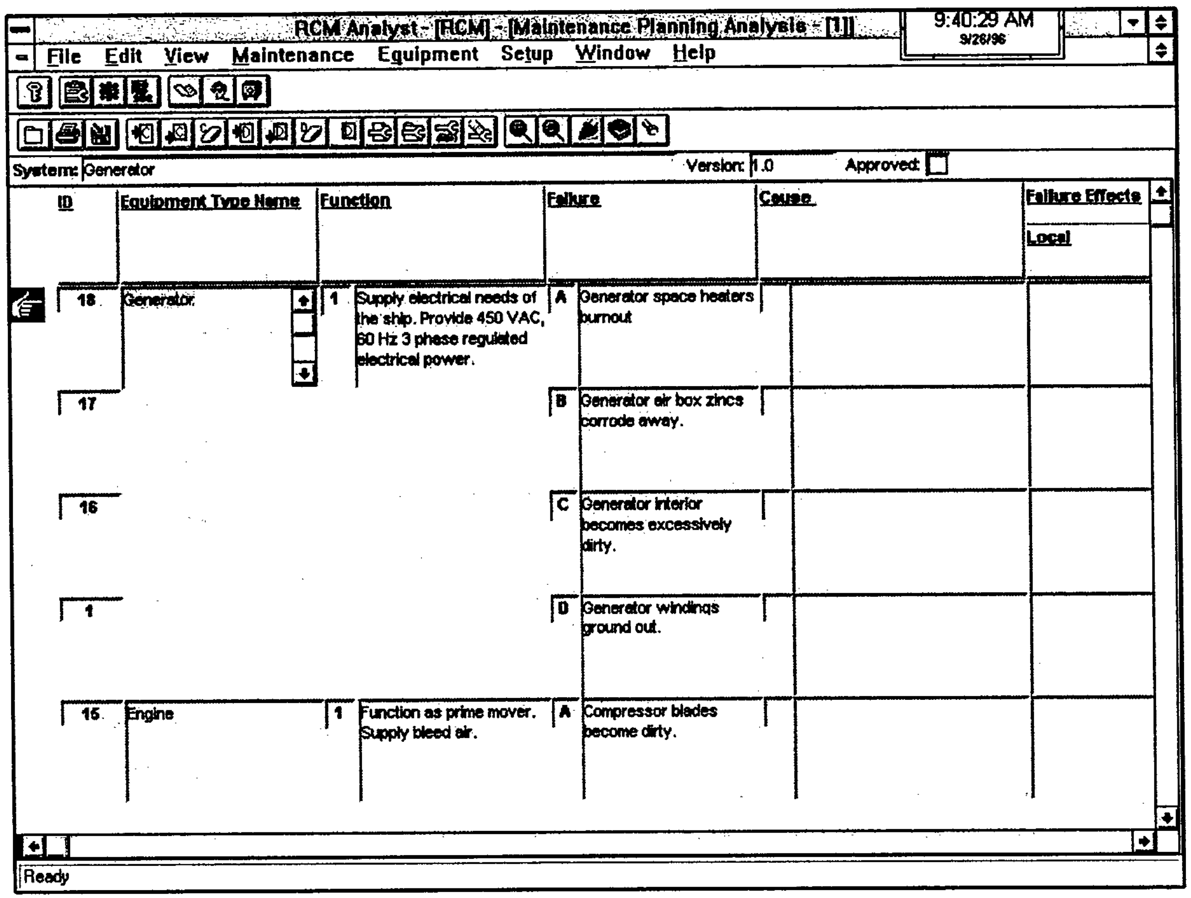
Maintenance Planning Analysis



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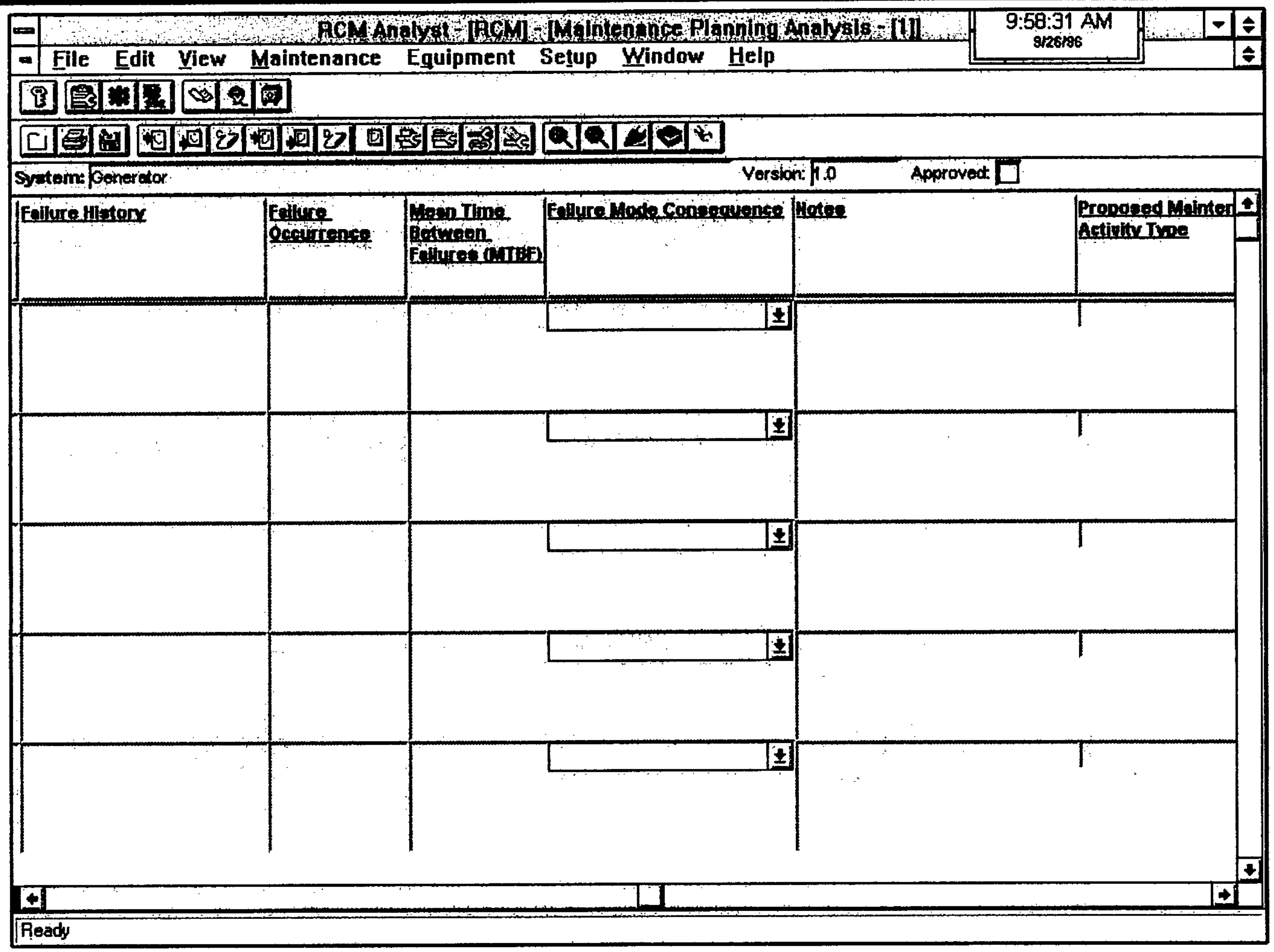
Maintenance Planning Analysis (Cont.)



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Current Status

- Preliminary FMEA input for 501-K34 Engine,
- Supporting data information book distributed to system user and manufacturer

RCM Summary

- What is RCM?
- Benefits:
  - Enhanced understanding of equipment operations,
  - Better understanding of failures and root causes,
  - Proposed tasks to maintain operation,
  - Improved operating output,
  - Lower costs,
  - Improved teamwork and motivation of personnel.
- Preliminary RCM Analysis for 501-K34 Engine

RCM Workshop Goals

- To develop list of potential ICHM applications for the 501-K34 SSGTG using:

    - RCM Information Book
    - RCM Analysis Worksheets
    - Your Experience

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Conduct of Workshop

Ground-Rules:

I. Failure Modes - List "Reasonably likely"

II. Team Approach - Consensus

III. Roles - System User, Manufacturer, Facilitator (Navy, Allison Engine Co., PSU)

IV. Scope - 501-K34 SSGTG

V. Goal - Potential ICHM Applications

Subsystem Leaders

Groups:

- Engine
- Accessory Drive
- Reduction Gear
- Generator
- Electrical Control System

Selection of Leaders will be based on:

- Expertise
- Familiarity with 501-K34
- Balancing Size of Groups

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Working Groups

Objectives:

1) Identify failure modes and effects for 501-K34
2) Assign criticality to each failure (suggestions):
   - Level One - failure has potential to seriously hurt or kill someone
   - Level Two - failure has potential to breach an environmental standard or regulation
   - Level Three - failure has potential to prevent mission
   - Level Four - failure has undesirable economic implications

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Some Final Considerations

Failures:

- Do not list every failure possible
- List probable failures
- Do not overlook “hidden” failures
- Determine end effects
- Note severity of failures

Potential ICHM’s:

- Failures
- Maintenance Plans
- Opportunities

APPENDIX D

501-K34 RCM WORKSHOP
Meeting Minutes
Appendix D
Parting Comments for The Good of The Order

Jim Donnelly:
1. Automating procedures to obviate need for PMS which causes faults and is dangerous.
2. Share information between electrical and mechanical systems especially for generator signal analysis.
3. [CBM diagnostics offers] Opportunity beyond maintenance cost avoidance.

Dick DeCorso:
1. Use performance data to avoid PMS, deal with real problems. Make system troubleshooting easier – built-in indicators.
2. Investigate start-up of engine problems (sometimes difficult to isolate whether it is the air system, starter, fuel air.)
3. Integrating sensor data on start air system.
4. Bearing monitors – focus on areas which are problematic "right now".
5. Improve basic performance monitoring – discriminate between turbine and compressor and determine when to water wash engine.

Jim Burns:
1. Cascading type problems – perform root cause analysis to determine who started problem primarily.

Tom Matella:
1. Better feedback on casualties to diagnostics; typically caught up in day-to-day and only hear chief complaints, i.e. can't drain the swamp.
2. DDG's don't have ICAS yet except *Sullivans*; get sailors thinking about ICAS.
3. Integration between mechanics and electronics is nonexistent except at higher level.
4. Will take these results back to Port Engineers meeting.
5. CASREP data back to ship is imperfect system – this addresses that.

Mike Mulkey:
1. If we proceed with this it will have benefits.
2. Saving money for the Navy is not the goal – bring it (ship) back home is the mission.
3. The generator, switchboard and distribution system is the heart and soul of the ship.
4. K.I.S.S.

Al Mancuso:
1. Overall sound approach. See temptation to overload GTG with too many sensors. Overload monitoring system with conflicting data.
2. Vibration and electrical data can concur or conflict (may be out 180 deg.) – use diagnostics to figure out data.
3. Monitoring electrical system for grounds and shorts is a good idea.
4. EMI causes 3-4K RPM indicator when turbine not running – logic open fuel valve at 1800 RPM.

Tien Phan:
1. Not sure how long this will take – example – ICAS is 9 years old.
2. Detect fuel in engine prior to start to avoid blowing out windows.

Vince Vizzard:
1. LOCOP data taken manually via serial port (with FADEC on DDG-86 ~ yr. 2001). Fleet evaluation on DDG-78 of FADEC 3/98.
2. Want to dissimminate the information from here.
3. Worked in vibration – don't always know.

Celena Cook:
1. Got an understanding that the system must be looked at as a system especially for diagnostic troubleshooting.
2. System that could tell where the problem is.

3. Give a better interface to get the level of expertise that Mulkey has into sailor. Just last week when changing out LOCOP there was a ground fault which took long time to determine.

Greg Colman:
1. Keep in mind that this will be a maturing system including rebellious teenage year.
2. Keep in mind it's a part of the CBM philosophy.
3. Include training and supply and logistics; eg. If we know bearing will last 37 hours, but takes 6 months to get – no good.

Tom Stordahl:
1. Ensure that we maintain system compatibility (i.e replacing generator, engine). Open Architecture.

Vern Holmes:
1. Make sure engine will start under adverse conditions. Allison is currently working on a system to connect a laptop PC to eliminate LOCOP under these conditions.

Al Federovich:
1. What powers the sensors? UPS for sensors.

Jeff Kohler:
1. Most useful two days in a few years.
2. Came away with a dozen or so problems that we can address.
3. Prediction algorithms to avoid getting caught with pants down.

Thom Galie:
1. Very pleased. Pulled together everything up to plant level.
2. Identified faults so we can show effects during demo [at LBES].
3. Want to use CBM philosophy to establish a systematic approach to improve process and policies.

Bill Masincup:
1. Pleased with discussion.
2. The number one CASREP's are SSGTG's on 963, 993, 47, 51. DDG-51 accounts for 24% of total CASREPS.
3. Do not stay in perpetual beta test!
4. Rules for diagnostics/prognostics need to be reviewed by a group like this.
5. Look at adding sensors also consider replacing "pressure" sensors with button.
6. Current problems – seawater in lube oil, water in starter system and fuel nozzles.

Chris Armitage:
1. Pleasantly surprised that we all recognized that we can not do everything - needed to consider probability as well as consequences.
2. Nothing should sacrifice operational, safety or environmental concerns.
3. Budgets will reduce, we should help the ships do what they're doing in the reduced budget environment.
4. Not a static thing, must go through an evolution and continue to review.

Scott Zerr:
1. What are we going to do with the numbers? Looks like this meeting is going down the right road.
2. Data acquisition system - Must be easy for guys on ships to work with.
3. Like the way Penn State is guiding us through the process.
4. Good dialogue at **meeting**.

Ben Wainscott:
1. Structure is OK for the amount of coverage. Had the right people, especially important to have fleet.
2. Taking on whole system rather than breaking into parts would have been better organization.
3. FTSCPAC goal is to have ship sail without CASREPS.

4. Should design out failures.
5. System can help fleet do PMS – if we can assist in performance analysis and make smart PMS decision and give fair warning of catastrophic failure.

Florizel O'Hara:
1. Pleased to meet with nucleus of naval engineers.
2. Thinks what we are trying to do will help the sailors.
3. Help bring ship back to mission capable status.

Steve Stephens:
1. Workshop should include more enlisted guys, have a question and answer session on how work will affect their life.

Final Report

"SHIPBOARD DEMONSTRATION OF A MACHINERY MONITORING SYSTEM"

Leslie D. Johnson and Terri A. Merdes
Applied Research Laboratory, Pennsylvania State University, University Park, PA 16804

Abstract: Machinery diagnostics and prognostics is an enabling technology for preventing equipment operational failures, reducing maintenance costs and improving system design. The Navy is currently investigating the impact of this technology for shipboard applications. A research team is currently participating in a shipboard demonstration of machinery monitoring system for a ships service gas turbine generator (SSGTG) set. The monitoring equipment was developed using modified commercial-off-the-shelf (COTS) technology to enable rapid revisions to the software as design requirements changed, with an open architecture to enable monitoring multiple components. A key focus of this study concerned the condition of the bearings and gears of the mechanical components as well as the electrical components such as windings and diodes.

Key Words: Health Monitoring System; Integrated Component Health Monitor; Ship Service Gas Turbine Generator; System Health Monitor

Introduction: The Pennsylvania State University Applied Research Laboratory (ARL) is currently performing an Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics (ACI), sponsored by the Office of Naval Research in the areas of reliability-centered maintenance, instrumentation, and machinery diagnostics and prognostics. Machinery diagnostics and prognostics is an enabling technology for preventing equipment operational failures, reducing maintenance costs, and improving system design. The Navy is currently investigating the potential of this technology for shipboard applications. A research team consisting of The Office of Naval Research, Naval Surface Warfare Center Carderock Division - Philadelphia, ARL, Renssalaer Polytechnic Institute, University of Kentucky, Oceana Sensor Technologies (OST), Rolls-Royce Allison, and RLW, are currently participating in a shipboard demonstration of a machinery health monitoring system (HMS) for ships service gas turbine generator (SSGTG) sets. Specific components for the SSGTG were selected based on a study conducted by ARL and the Navy including life cycle managers, design engineers, sailors, and port engineers along side both the Pacific and Atlantic fleet's technical services engineers [1].

The goal of the ACI was to develop a hierarchical architecture to implement machinery monitoring at the machine, component and system levels. The ACI demonstrated the architecture at the intelligent node (wireless technology), system and platform level. Most of the hardware and software development however, focused on the intelligent node level. The intelligent node enables machinery health monitoring of particular machinery components. The purpose of the machinery Health Monitoring System (HMS) was to obtain as much data and information at the component level as possible, and to transmit potential alert and alarm messages to the ship's crew onto a display station.

An important task for transition of the ACI technology was to acquire realistic data to validate the algorithms and hardware/software for fleet implementation. For transition, emphasis was placed on validation of the ACI-developed hardware and software. The validation phase focused on data acquisition at the Philadelphia Land Based Engineering Site (LBES), algorithm validation on test rigs, testing on the electrical generator, and accessory gearbox rigs to provide fusion of vibration data with electrical subsystems. The ACI concluded with a shipboard demonstration of the developed technology. This included developing appropriate technical specifications, obtaining approval and support from equipment owners, and implementing the technology based on ship availability.

A study [1] based on reliability-centered maintenance principles produced a number of components to instrument. In particular, many of the signals that were originally identified as monitoring applications are actually included in the control system. Of the original areas selected, only the generator (electrical and mechanical systems), the reduction gearbox and the accessory gearbox, remained as candidates for using intelligent nodes. (See Figure 1)

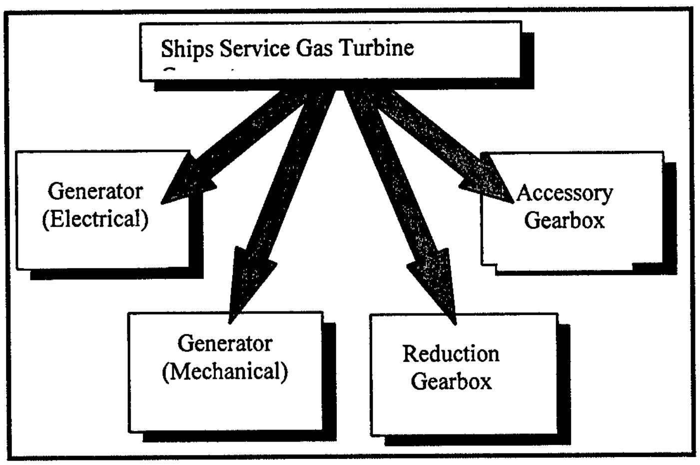

Figure 1. SSGTG Monitored Components

Health Monitoring System: The machinery health monitoring system is shown in Figure 2 and employs a data fusion capability [2]. Data is processed and fused at both the ICHM and SHM level. At the ICHM level, sensor data is first converted to engineering units, then processed using filtering, FFTs, wavelets or other techniques to enhance the signal to noise ratio and to extract signal features indicative of component health. After initial processing, thresholding or other techniques are used to determine whether the sensor indicate the onset or progression of damage. Kalman filters are used to smooth the data and predict the future values of the features.

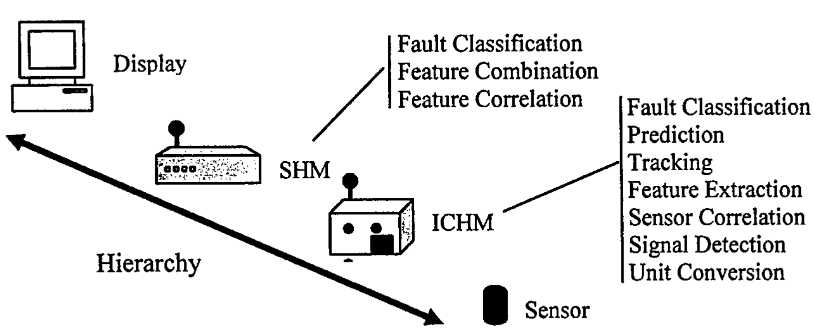

Figure 2. Machinery Health Monitoring System – Data Processing and Fusion

At the SHM level, features from multiple ICHMs can be correlated and combined, then input to fault classification algorithms. In some cases, different ICHMs may have redundant sensors whose data can be correlated to improve the reliability of the measurements and detect sensor problems. The machinery health monitoring system includes some ICHMs that may provide overlapping information at the same ICHM level – for example, each of the four accelerometers mounted on the reduction gearbox will measure (to some extent) the same vibration signals. The machinery health monitoring system can also employ fuzzy-logic to classify machinery fault conditions.

The machinery HMS was completely installed on the *USS Fitzgerald* (DDG-62), an *Arleigh Burke* class guided missile destroyer home ported in San Diego California. The *USS Fitzgerald* is a guided missile destroyer, commissioned in 1995 and is homeport in San Diego, California. There are three Allison 501-K34 SSGTGs; on board that supply electrical power to the ship. During normal steaming, two of the turbines are kept operational with the third standing by as backup.

The components of the machinery HMS installed on the *USS Fitzgerald*, are shown in Figure 3, and consist of:

- 4 ARL intelligent component health monitoring systems (ARL-ICHM)
- 1 ICHM.20/20 and Dongle developed by OST (hardware) and RLW (software)
- 1 ARL System Health Monitoring system (SHM)
- 1 ARL designed power supply unit

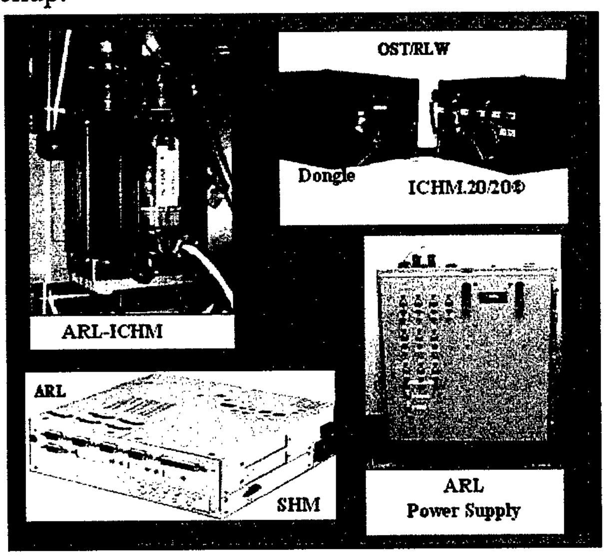

Figure 3. Health Monitoring System

The lowest levels of the ACI hierarchical architecture for machinery health monitoring system are the ICHMs. The ICHM collects data from the sensors and performs calculations on the data to provide an indication of the component health to the SHM. Each of the four rugged PC-104 based ARL Integrated Component Health Monitors (ICHMs) utilizes a Proxim radio operating at a carrier frequency of 2.4 GHz, and is fabricated by integrating commercially available components (such as CPU and analog to digital converter boards), with an ARL-designed signal conditioning board. The custom signal conditioning board provides power to ICP™ accelerometers, anti-alias filtering for acceleration and temperature measurements and permits monitoring sensor bias voltages for an indication of sensor health. Each ARL-ICHM is capable of collecting five channels of data at a maximum aggregate sampling rate of 200 kHz from the measured components, performing calculations, and running algorithms on the data to provide an indication of the component health to the system health monitor. It also has the capability of being field programmable to permit upgrades to data analysis and other functions. A watchdog was incorporated into the design to allow the system to restart in the event of a power loss. A metal container using military specified connectors for data acquisition and power houses the internal components. More specifically, the functions of the ICHM include:

- Data acquisition
  - Data acquisition from temperature and vibration sensors
  - Signal conditions (e.g., sensor power, filtering, amplification)
  - Data conversion (multiplexing, A/D conversion)
  - Generated test and calibration signals
  - Data analysis with alert and alarm messages
- System support
  - Controls communication, data acquisition, data analysis, system clock
  - Windows NT
  - ICHM self-diagnostics, watchdog timer control
  - Physical interfaces (keyboard, video, mouse and com ports.)

The OST/RLW ICHM.20/20 utilizes 2.4 GHz Bluetooth™ wireless technology, while processing data on a Sharc DSP. This unit has one high-resolution channel (24-bit, AC-coupled, sample rate 4-48 kHz), and one low-resolution channel (12 bit, DC-coupled, analog input, sampling under software control). The shipboard designed ICHM.20/20 wirelessly passes data and receives information queries from the System Health Monitor (SHM) via a Dongle, which is RS-232 serial ported into the SHM.

The SHM receives input from multiple ICHM units to reduce false alarms and to improve the reliability of the alert and alarm information being supplied to the crew via a display station. The SHM also stores the raw data from the ICHM units for future data analysis. The SHM includes:

- System hardware
  - 233 MHz Pentium processor
  - 156 megs of RAM
  - NT4 operating system
  - Proxim radio
  - Keyboard, video, mouse and com port interfaces

A stand-alone power supply unit was designed and developed by ARL, to ensure delivery of proper power levels to the ICHM's and to the SHM. This power supply unit also has a thirty-minute battery backup in the event that the ship should lose power.

ICHM Monitoring Capabilities: Figure 4 shows the top-level view of the system. Overall system health and status are derived from the health and status of the functional subsystems, which comprise the system. For the purpose of the ACI demonstration, the gas turbine generator is broken down into four subsystems: the generator, the reduction gearbox, the accessory gearbox, and the engine. The engine includes the compressor and the turbine.

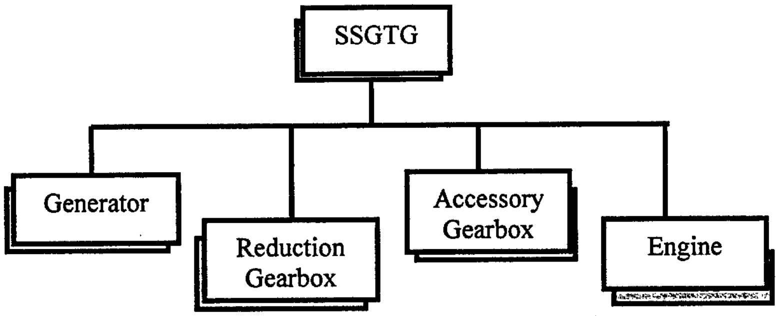

Figure 4. Overview of Monitored Systems

The 501K-34 generator used in the SSGTG can be subdivided into two types of components, (electrical and mechanical) and is monitored by two separate ICHMs, see Figure 5. ICHM 1 monitors the electrical components of the generator, which include the stator windings, field windings, and the rectifier diode used in the exciter circuit. This is accomplished by measuring each phase of the output voltages and currents along with the exciter current and voltage. To ensure the health of the ICHM, internal temperature is also measured. ICHM 2 monitors both the vibration and temperature levels on both the drive-end and the permanent magnet assembly (PMA) end of the generator, with two accelerometers/temperature sensors placed 90 degrees apart on each end. The bearings associated with the generator are journal bearings, and although accelerometers would not be a likely candidate to measure the health of these bearings, it was decided that in the event of a catastrophic bearing failure or an electrical failure, monitoring the effects of one component on the other could be beneficial in evaluating the health of the

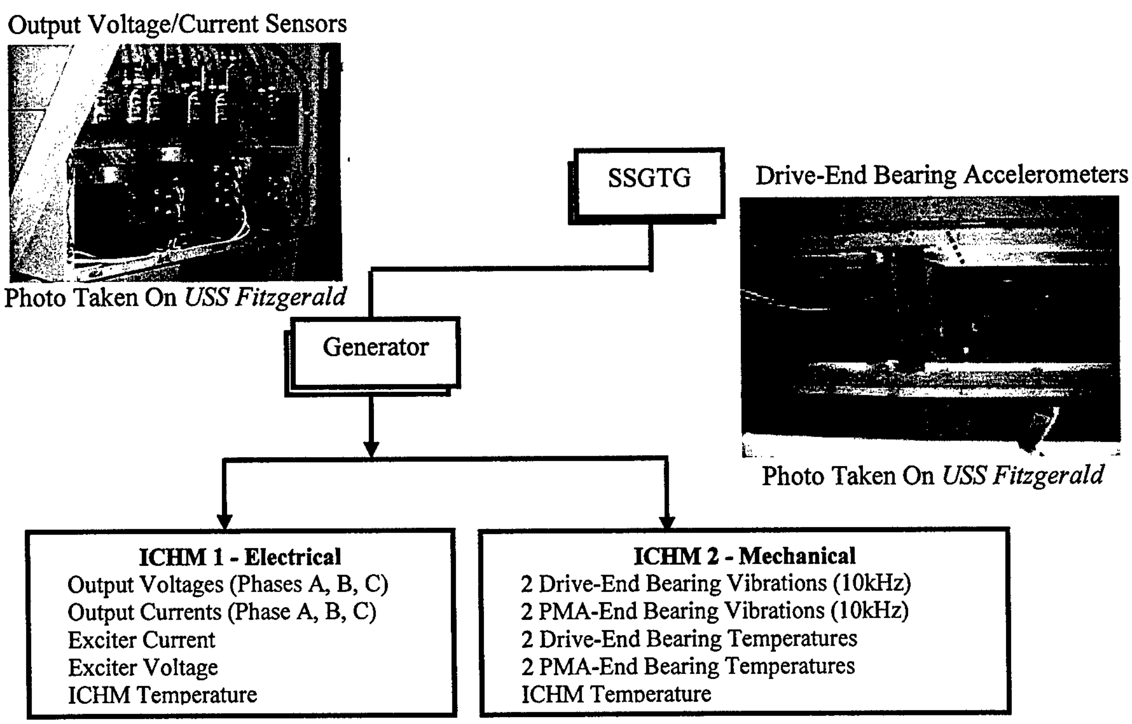

Figure 5. Generator Data Collected From ICHMs 1&2

generator. Bearing temperatures are also being measured to track the temperature of both the bearings. Both ICHMs are mounted outside of the gas turbine engine module in the engine compartment, and therefore are only subjected to the temperature ranges in the engine compartment.

Shown in Figure 6, the reduction gearbox is monitored by ICHM 3 which is mounted inside of the gas turbine engine module and which is subjected to the temperatures of that environment. Because of the possibility of the compartment reaching temperatures near the critical operating temperature of the ICHM, internal ICHM temperatures are continuously monitored. The reduction gearbox consists of a high-speed shaft and pinion that drives a low-speed shaft and gear assembly that drives the generator. Four accelerometer/temperature sensors are used to measure both vibration and temperature for each of the following components: the high-speed shaft and pinion, the high-speed non-drive-end shaft, the low-speed shaft and gear, and the low-speed non-drive-end shaft. This configuration allows data to be collected not only to determine the health of the gears, but also to aid in the understanding of how failure from either the generator or the engine can affect the reduction gearbox.

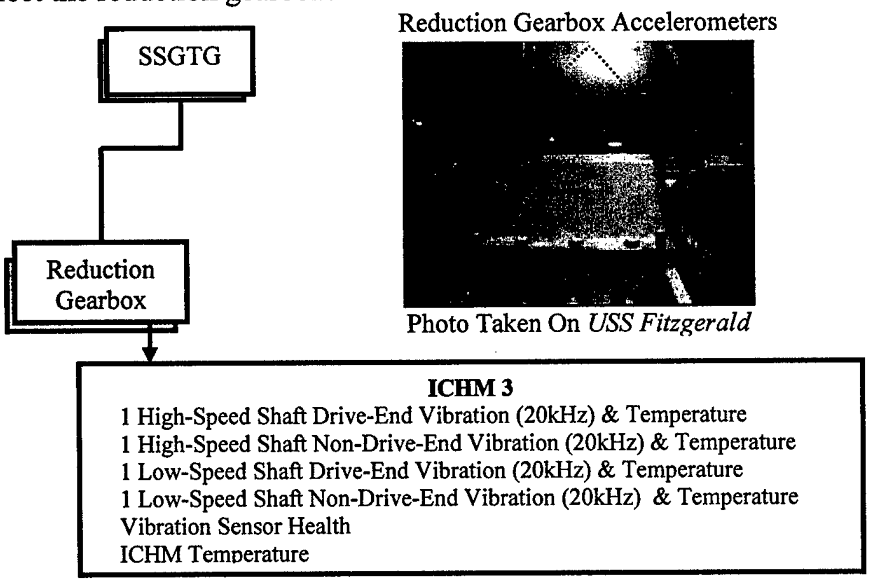

Figure 6. Reduction Gearbox Data Collected From ICHM 3

ICHM 4 is mounted inside the gas turbine engine module and therefore like ICHM 3 is exposed to higher engine temperature and is also continuously monitored. As seen in Figure 6, one accelerometer/ temperature sensor is mounted on the top of the inlet housing to monitor the compressor bearings and shaft vibrations along with the compressor surface temperature. The accessory gearbox has a triaxial accelerometer mounted on its midsection on the underside. The accessory gearbox is a complex component that controls the fuel pump, oil pumps, possible tachometer, and governor. Although this gearbox provides a challenge for data processing, it is essential since the Navy is currently investigating extending its life.

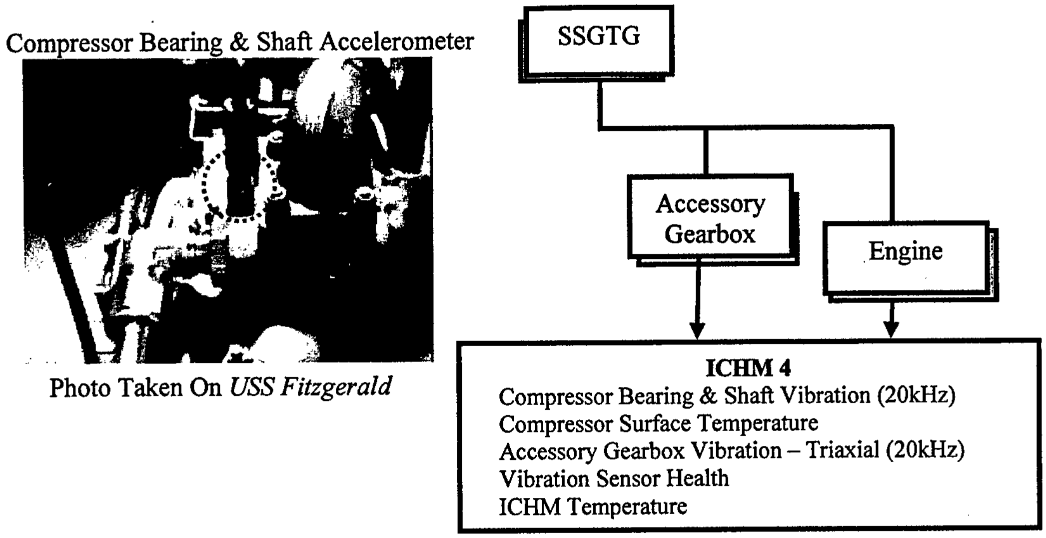

Figure 7. Accessory Gearbox & Engine Data Collected From ICHM 4

Preliminary Data Findings: A 5KW scale model of the 501-K34 has been designed and delivered to ARL, by the University of Kentucky, providing a means to simulate the generator onboard a ship with, either or both, mechanical and electrical faults. In addition, a high-speed accessory gearbox rig is currently under construction to assist in initial tests of the intelligent component health monitors and to accurately determine the characteristic frequencies of the gearbox under loading conditions. Data were also collected at the LBES on both the K17 and K34 SSGTGs during an integrity test of the HMS, which was necessary for the approval process to gain access to a US Naval ship. The K17 was similarly instrumented and monitored under the Reduced Ships-Crew by Virtual Presence (RSVP) program [2] sponsored by Jim Gagoric, ONR Code 334 on the *USS Monterey* (CG-61) in February 2001.

Data collected on test rigs, at the LBES, and on the previous ship install enabled the determination of operating values for the generator voltages and currents, including ranges for the various accelerometers on the accessory and reduction gearboxes. Table 1

Table 1. Monitored Components and Data Sources

	USS Monterey K17 Underway	NSWCCD LBES K17	USS Fitzgerald K34 Underway	NSWCCD LBES K34	PSU/ARL Generator Test Rig	NSWCCD Allison 501K Seeded Faults	PSU/ARL High Speed AGB Test Rig
Generator Electric	Yes	Yes	First Qtr 2002	Yes	Yes 07/23/01	—	—
Generator Mechanical	Yes	Yes	First Qtr 2002	Yes	Yes 07/23/01	—	—
Reduction Gearbox Mechanical	Yes	Yes	First Qtr 2002	Yes	—	—	—
Accessory Gearbox/Engine Mechanical	Yes	Yes	First Qtr 2002	Yes	—	Yes Only AGB	Under Construction

shows the relationship between the components monitored and the various data collection sources. This data also provided frequency spectra to support algorithm development for installation on the *USS Fitzgerald* (DDG-62).

As an example when looking at a feature comparison from the LBES 17 data vs. the Monterey K17 underway data on the reduction gearbox, similarities were found under identical load and power factor conditions. The Crest Factor feature for the LBES fits very well within statistics, as seen in Figure 8.

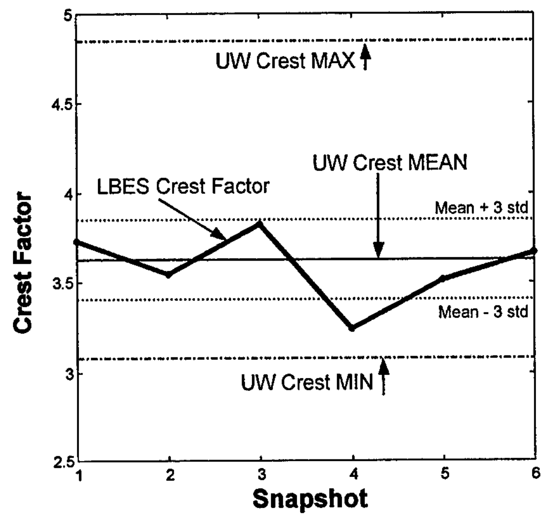

Figure 8. Crest Factor on Reduction Gearbox (Comparison)

Similar results were found for other feature comparisons. Table 2 depicts which LBES feature data means are within 1-3 standard deviations of the underway feature data means, when using the same preprocessing parameters and techniques. Several features do not behave similarly and require further investigation.

Table 2. LBES K17 Features vs. Monterey K17 Underway Statistics

	Ch#	RMS	Skew	Crest	Kurt	EnvKurt	EnvPk	EnvFrq	DemPk	FM0	SLF	S01	S02	M6A	M8A	FM4
Elect. Generator	1															
	2															
	3															
	4															
Mech. Generator	1	1		3			1	1	3	1	3		1	1	1	1
	2	3		3	3	3	3	1	3	3		1	1	1	1	1
	3			3	1		3			3	3	1	1	1	1	1
	4		1			3	3	1		3	3	3	1	3	3	3
Reduction Gearbox	1			3	3	3	3								3	
	2		3	3		3	3		1						3	
	3			1			3	1	3	1	1					
	4	1	3	3			3	3	3				3		3	
Eng	1	3		1	3											
Acces. Gearbox	2			3	3											
	3															
	4			3												

The key result is the similarity of the features calculated on LBES and shipboard data, and indicates the value of the Philadelphia LBES test facility in refining the algorithms necessary for shipboard applications.

Conclusions: The effort described in this paper illustrates the technical challenges involved in performing an actual demonstration of condition monitoring for a shipboard application. During each phase of the effort, from development of the intelligent nodes, selection of the components to be monitored, preliminary tests and shipboard installation valuable lessons were learned. For example, during the study some components that were not recommended to be monitored, were recommended to be redesigned. The purpose of machinery monitoring is to manage those components that are deemed critical with regard to mission, and consequences such as loss of life, performance, and/or cost. Based on the preliminary findings, installing health monitoring systems is feasible and beneficial for complex equipment such as generators, turbines and gearboxes. A critical need for complete validation of this technology is the acquisition of more data from multiple machines. Future monitoring systems should be "built-in" from initial design to minimize the installation difficulties. Another future application would be to combine the health monitoring data with the control system data. This data would not only improve the accuracy of algorithms but also lay the foundations to transition from diagnostics and prognostics to intelligent control.

Acknowledgements: This work was supported by The Office of Naval Research Grant, An Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics, N00014-96-1-1147, the content of this paper does not necessarily reflect the position or policy of the Government, and no official endorsement should be inferred. The authors would like to thank Dr. McKenna, ONR Code 342 for sponsoring this research, the Engineering staff at NSWCCD Philadelphia for installation and technical support, the Captain and crews of the USS Monterey and USS Fitzgerald for technical assistance and the ACI Team members for their dedication to this research program.

Feature Extraction Technique Definitions:

RMS – Root Mean Square is a time analysis feature that measures the power content in the vibration signal.

Skew – characterizes the degree of asymmetry of a distribution around it means.

Crest – a simple approach to measure defects in the time domain using the RMS approach.

Kurt – kurtosis is the fourth moment of the distribution and measures the relative flatness of a distribution as compared to a normal distribution.

Enveloping – used to monitor the high-frequency response of the mechanical system to a periodic impact such as gear or bearing faults.

EnvKurt - performs enveloping then kurtosis techniques.

EnvFrq – performs enveloping technique then looks for the frequency at the highest peak.

DemPk – demodulation identifies periodicity in modulation of the carrier.

FMO – is a method used to detect major changes in the meshing pattern.

SLF – is the sideband level factor and is used to detect a bent or damaged shaft.

S01 & S02 – are the first and second shaft order vibration amplitude levels (respectively) and is used to detect shaft imbalance or damage.

M6A & M8A –detect surface damage on machinery components.

FM4 –detect changes in vibration pattern resulting from damage on a limited number of gear teeth.

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Accelerated Capabilities Initiative in Machinery Diagnostics and Prognostics II (Transition Plan: Final Validation)

July 19, 2001

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INTRODUCTION

This paper describes proposed work to be conducted at the Applied Research Laboratory of The Pennsylvania State University. The following work is proposed for FY02 to validate the algorithmic technologies demonstrated in the Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics (ACI) Program. Since the hardware and software have been developed and demonstrated, validation is the final impediment to full fleet transition of the technology.

BACKGROUND AND RELEVANT WORK

The Applied Research Laboratory has a number of active projects in the areas of reliability-centered maintenance, instrumentation, machinery diagnostics and prognostics. For example, the department is currently performing the Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics (ACI), sponsored by the Office of Naval Research (Dr. Thomas McKenna Code 342). The goals of this program is to develop a hierarchical architecture and demonstrate machinery health monitoring on a ships service gas turbine generator set (SSGTG). The generator set supplies electrical power to ship systems on board Arleigh Burke class destroyers (Figure 1).

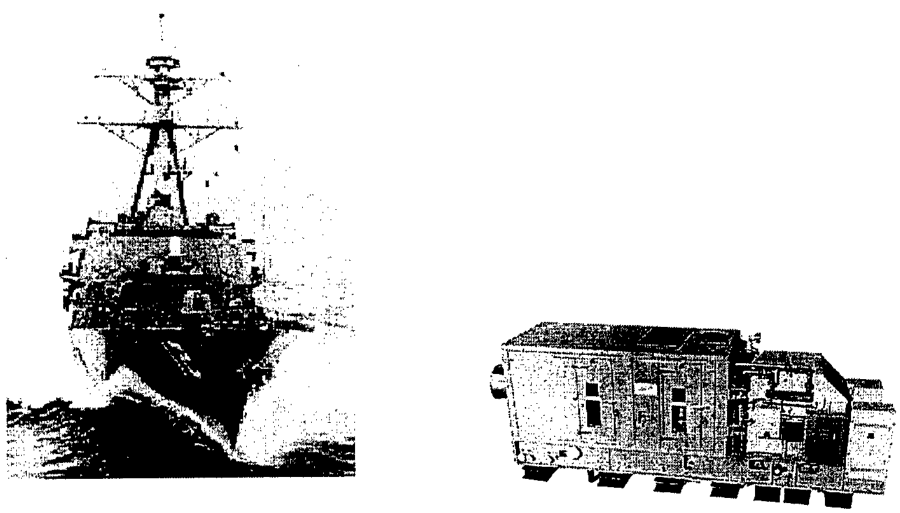


Figure 1 - Arleigh Burke Class Destroyer and Allison 501-K34 SSGTG

The ACI Program had its beginnings in the MURI program. The MURI concepts of sensing, modeling and reasoning and the hierarchical architecture for CBM was developed. With the award of the ACI in mid-1996, starting from only concepts and ideas, the team developed prototype hardware and software to implement the 3-layer architecture for application to the 501-K34 SSGTG. Prototype hardware was produced by OST (self-cal sensor) and Invocon (breadboard and brassboard hardware). In parallel with the hardware development, algorithms and software were developed, resulting in an operational intelligent node with running software in late 1999. The results of the RCM analysis have not only defined the current instrumentation plan; this information is also being implemented (in a separate Navy project) to automate water washing based on compressor performance (identified at the 1997 workshop). Also, the ability to send information from the ACI architecture into the Navy integrated and Condition Assessment System (ICAS) was demonstrated in early 1999. Preliminary tests with the wireless hardware were conducted in field tests and at the land-based engineering site (LBES) in Philadelphia to verify equipment operation. A unique scale model of the generator was constructed to investigate generator diagnostics.

The ACI also supported a number of software toolkits, potentially leading to commercial software products. The results of ACI I were supplemented with the development of additional test rigs and actual data acquisition at LBES.

The ACI project has produced a number of successful products. For example, the program has produced prototype hardware and software to implement machinery health monitoring and enabling prognostics and health management. The research team includes organizations for academia, industry and Navy.

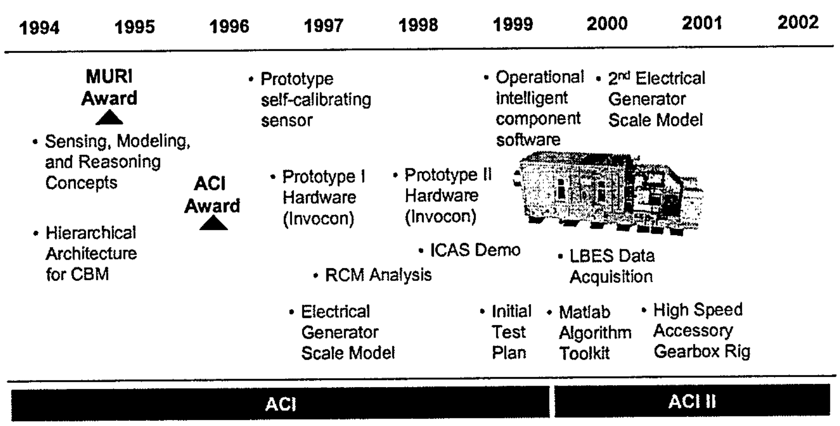
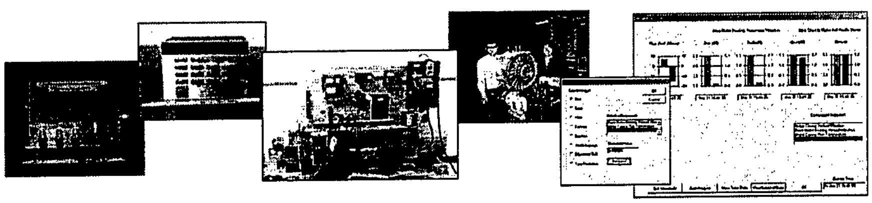


Figure 2 – ACI Outcomes

ACI ACCOMPLISHMENTS

Key accomplishments of the ACI included prototype hardware to support the 3-layer architecture and, even more importantly, the open systems software that allows the software to be ported to multiple hardware platforms. Since the prototype hardware consisted of a proprietary radio network, the value of the flexibility of the software is being realized, as the software can run on many hardware devices. Also critical is the establishment of test facilities unique to machinery diagnostics and prognostics. There are only two 501-K electrical generator models in existence (University of Kentucky and PSU). These facilities enable the ACI team to act as "trusted agents" and provide transitional data to other organizations. The test experience and lessons learned are of great value since they contribute to hardware and software that perform well in realistic environments. Major accomplishments in the area of technology are cited, including team members becoming active in other research projects involving machinery diagnostics, the development of intelligent node requirements and a partnership with NSWCCD Philadelphia for implementing the ACI technology in CBM and training.



Prototype hardware – to support three-layer hierarchical architecture

Open systems software – algorithms that are portable to multiple hardware platforms

Test facilities unique to machinery diagnostics and prognostics – enable ACI team to act as "trusted agents" and provide transitional data to other organizations

Valuable test experience and lessons learned

Technology transfer

- Spin-off test experience and diagnostic algorithms
- Development of intelligent node requirements
- NSWCCD Philadelphia partnership for CBM implementation and training

Figure 3 – ACI Accomplishments

The ACI has completed hardware and software design with the development of various hardware solutions for the intelligent component health monitor. This hardware and software has been installed on the USS Fitzgerald (DDG-62). The stage is finally set for the program to focus on the performance of the algorithms and reasoning concepts developed under the MURI and ACI programs. True implementation of the ACI technology to the fleet will not be complete without successful validation that the algorithms and reasoning approaches actually work reliably. Validation will not only enable successful transition, but will also provide a foundation for machinery prognostics as it applies to engineering design and asset readiness.

The ACI demonstrated the architecture at the intelligent node, system and platform levels. Most of the research efforts have focused on development of hardware and software and algorithms at the lowest level of the architecture. System level fusion has focused on the distinction between electrically-excited vibrations and bearing vibration to reduce false alarms. However, in order to realize the full potential of machinery diagnostics and prognostics for automation and asset readiness, the system level intelligence must be validated.

VALIDATION PROGRAM

The validation is proposed to consist of testing and experimentation, performance assessment of the algorithms, and application of classifiers, fusion and reasoning to this data to prove the worthiness of the architecture for full fleet-wide implementation.

PROPOSED TASKS

In order to accomplish validation the following tasks are required:

TASK I – EXPERIMENTAL TEST DESIGN

A series of tests will be conducted using the design of experiments approach. This approach ensures replications of the investigations, yielding reliable findings. The unique test beds for this research have already been constructed enabling hardware and construction costs to be minimized. These test rigs include but are not limited to: a 501-K34 scale generator model; a high speed accessory gearbox rig; a diesel engine test bed; a lubrication system, test bed and a battery diagnostics lab, and a new oil analysis lab.

TASK II – ALGORITHM VALIDATION

1. Test Rig Validation. Tests will be conducted on the high speed accessory gearbox rig and the 501-K34 scale electrical generator rig to determine the performance of various bearing and gear algorithms developed under the ACI and MURI programs at PSU to determine the algorithms suitable for running at LBES. The rigs will enable accurate identification of potentially trackable features for enabling prognostics. Those algorithms that work reliably with good confidence will be transitioned to the LBES for inclusion into the FADC (FADC efforts are planned to be funded by NSWCCD Philadelphia).

2. LBES Validation. Using data acquisition equipment awarded by the Defense University Research Instrumentation Program data will be acquired in "piggy-back" mode (i.e. taking data during regularly scheduled tests or training exercises) on the

SSGTG at LBES. Since training and other engineering tests are ongoing at LBES significant cost savings in fuel and labor will be realized. Test log sheets and data CD's will be provided by NSWCCD to PSU for analysis. The analyzed data will be compared to the shipboard data in Task III below. Ranking criteria for measures of effectiveness and measures of performance will be used for this task.

TASK III – SHIPBOARD DATA ANALYSIS
The data from the machinery health monitoring equipment currently installed on the USS Fitzgerald (DDG-62) will be analyzed using the existing algorithms providing actual shipboard data to support future prognostic research efforts.

TASK IV – CLASSIFIERS, FUSION AND REASONING
Using the results of the experimental tests and algorithm validation, higher level reasoning approaches will be applied using the above test data to determine approaches such as classifiers, fusion and reasoning that perform reliably for machinery diagnostics and prognostics. A study in noncommensurate data fusion will be included to combine test rig data with oil and acoustic emission data.

TASK V – TECHNICAL REPORTING AND PROGRAM MANAGEMENT
Program Management – This task will provide correspondence with the sponsor to ensure program objectives will be achieved. A quarterly report will be provided summarizing technical challenges and major accomplishments. A final report on the assessment of the performance of the condition monitoring system and algorithms will be provided.

RELATED EFFORTS/BENEFITS
Other Programs
The proposed effort would be of benefit to the proposed Navy Gas Turbine Transition Plan as well as a proposed DARPA Program in Asset Readiness. The Navy plan includes the upgrade of the FADC for the Allison 501-K series and the GE LM2500 engines. These engines comprise a large part of the Navy shipboard requirements for electrical power generation and propulsion. The proposed effort also offers the opportunity to exercise the capabilities of the Advanced Sensors and Control Evaluation Laboratory awarded under the Defense University Research Instrumentation Program (DURIP).

RESEARCH TEAM
The research team consists of current ACI Team Members. Rolls Royce Allison will provide technical support regarding the design configuration via the existing Component Improvement Program contract with NSWCCD. Finally, NSWCCD will provide LBES facilities and assist in shipboard demonstration. The University of Kentucky and Rensselaer Polytechnic Institute and PSU will support assess the performance of the algorithms and investigate classifiers, fusion and reasoning for the system level.

PRINCIPAL PERSONNEL

Les Johnson has been a Research Assistant at the Applied Research Laboratory since 1991. Currently, he is the Department Head of the Advanced Sensors and Control Department. Mr. Johnson has an interest in mechanical design, failure analysis and control systems. He holds a BS Degree from Drexel University in Mechanical Engineering and an MSE Degree from the University of Pennsylvania in Mechanical Engineering and Applied Mechanics. He is a member of ASME and ASHRAE professional engineering societies. Mr. Johnson is also a licensed Professional Engineer in the state of Pennsylvania. Most recently, Mr. Johnson received a DURIP award for the Advanced Sensors and Control Evaluation Laboratory.

Karl Reichard has been a Research Associate at the Applied Research Laboratory since 1991. Currently, he is also the Deputy Department Head of the Advanced Sensors and Control Department and an active participant in the ACI Program. Dr. Reichard's experience has included hardware and software system design and development for intelligent, networked sensor systems for machinery condition monitoring and surveillance applications. His work has included development and application of acoustic sensing and signal classification techniques for machinery condition monitoring and target identification. He has been involved in the development and implementation of adaptive signal processing and control systems for active noise and vibration control; and design, construction and testing of optical fiber and piezoelectric sensors for structural monitoring and control. Karl Reichard holds a B.S., M.S., and PhD Degrees in Electrical Engineering from Virginia Polytechnic Institute & State University.

Terri Merdes has been an Assistant Research Engineer at the Applied Research since 1997. Currently, she is Test Manager of the System Operations and Automation Division and an active participant on the high-speed accessory gearbox test rig. She also has test experience in oil analysis and borescope measurements. Terri is currently an MS candidate in the Quality and Manufacturing Management Program at Penn State. Ms. Merdes holds a B.S. in Mechanical Engineering from Penn State University.

C. James Li, Associate Professor of Mechanical Engineering, RPI

Dr. Li received a B.S. (National Taiwan University, 1980); Ph.D. (Univ. of Wisconsin-Madison, 1987) degrees, all in Mechanical Engineering. Dr. Li has expertise in Mechanical Diagnostics & Prognostics, System Identification, Automatic Control. He was an assistant professor at Columbia University from 1987 through 1992 and was promoted to associate professor in 1993. Dr. Li joined RPI in 1993. Dr. Li has served as a consultant for 6 industries (including GE-CRD, Mechanical Technology Inc., and SME). His research interests include nonlinear model-based mechanical diagnostics and prognostics, and nonlinear control of manufacturing equipment/processes in which he has published more than 35 refereed journal papers and 55 conference papers. He delivered dozens of invited lectures at universities, government laboratories, companies and professional meetings in and outside the US. Dr. Li has been principal investigator on contracts and grants in his research areas from governmental agencies including NSF, ONR, NYSERDA, NSWC and from such companies as IBM, AT&T, Textile/Clothing

Technology Corporation, and SME. He is a member of Vibration Institute and ASME where he served as a Dynamic System and Control liaison of the Manufacturing Engineering Division between 94 and 97 and is the Chair of Technical Committee on CIM and Robotics, Manufacturing Engineering Division since 97. Dr. Li's related research accomplishments include the development of neural networks for nonlinear and dynamic sytems, signal processing algorithms for bearing and gear condition monitoring, diagnostic extraction and prediction of component residual life.

Joseph Sottile received the B. S., M. S., and Ph.D. degrees in mining engineering from The Pennsylvania State University, University Park, in 1984, 1987, and 1991, respectively. He has worked in production and engineering for the Barnes and Tucker Company from 1977 to 1983, and for Consol, Inc., in 1987. He is currently an Associate Professor of Mining Engineering at the University of Kentucky, Lexington. His teaching and research interests include electrical applications in the mining industry. Dr. Sottile is the Past Chairman of the IEEE Industry Applications Society Mining Industry Committee. Most recently, he has been involved in the development of algorithms for the early detection of electrical winding deterioration in the AG9140 generator as part of the ACI project.

BUDGET

Estimates for the proposed effort (FY02) are as follows:

Team Member	Amount
NSWCCD	$ 60K
RR Allison Engine	$ 20K (Via NSWCCD CIP Contract Mod.)
University of Kentucky	$ 60K
RPI	$ 90K
PSU ARL	$ 580K
Total Team Funding:	$ 810K

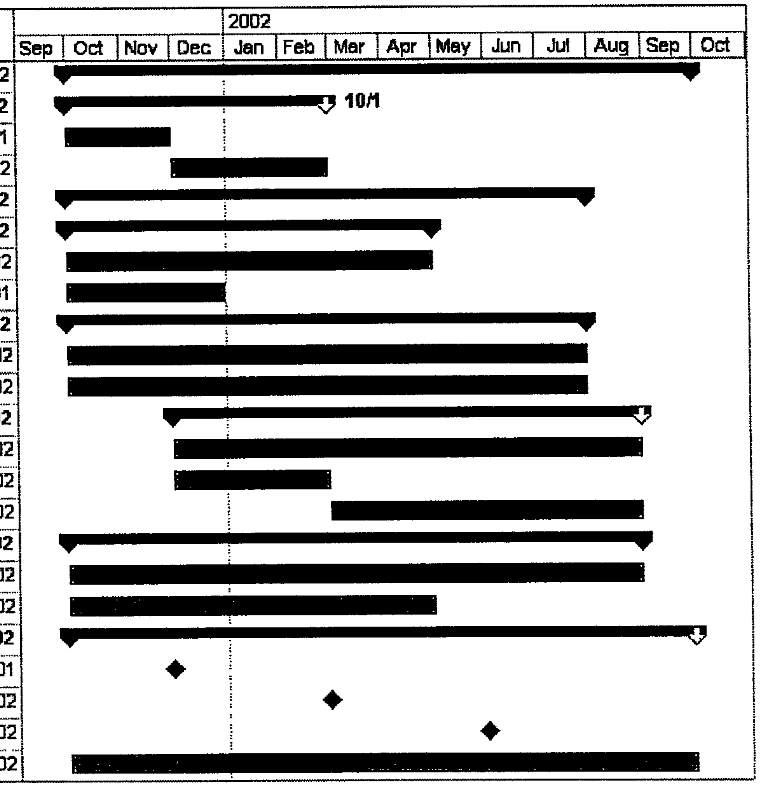
PRELIMINARY ESTIMATE
FY02 ACI II VALIDATION PLAN (10/1/01 Start to 09/30/02)

TASKS	1st	2nd	3rd	4th	PSU	RPI	UofK	Allison	NSWCCD
I. EXPERIMENTAL TEST DESIGN									
Test Plan Design					$15K				
Instrumentation Set-up for multiple test beds					$30K				
II. ALGORITHM VALIDATION (MOE/MOP)									
TEST RIG VALIDATION									
Accessory Gearbox					$90K	$10K			
Electrical Generator					$50K				
LBES VALIDATION									
Accessory Gearbox					$30K	$10K			$40K
Electrical Generator					$30K				
III. SHIPBOARD DATA ANALYSIS									
Install USS Fitzgerald (DDG-62)					--				
Collect information					$10K			$10K	$10K
Analyze information					$65K	$10K	$10K		
IV. CLASSIFIERS, FUSION AND REASONING (SHM)									
Develop data fusion module for monitored components					$120K	$50K	$50K		
Noncommensurate Data Fusion Study (Oil, AE with above)					$ 55K	$10K			
V. TECHNICAL REPORTS AND PROGRAM MANAGEMENT									
Report (12/01, 3/02, 6/02)					$ 10K				
Program Management					$ 45K			$10K	$10K
					$580K	$90K	$ 60K	$20K	$60K

ESTIMATED TOTAL: $810K

PRELIMINARY ESTIMATE
FY02 ACI II VALIDATION PLAN (10/01/01 Start to 09/30/02)

ID	Task Name	Duration	Start	Finish
1	**TASKS**	265 days	Mon 10/1/01	Mon 9/30/02
2	**I. EXPERIMENTAL TEST DESIGN**	**111 days**	**Mon 10/1/01**	**Thu 2/28/02**
3	Test Plan Design	45 days	Mon 10/1/01	Fri 11/30/01
4	Instrumentation Set-up for multiple test beds	66 days	Sat 12/1/01	Thu 2/28/02
5	**II. ALGORITHM VALIDATION (MOE/MOP)**	**221 days**	**Mon 10/1/01**	**Tue 7/30/02**
6	**Test Rig Validation**	**155 days**	**Mon 10/1/01**	**Tue 4/30/02**
7	Accessory Gearbox	155 days	Mon 10/1/01	Tue 4/30/02
8	Electrical Generator	67 days	Mon 10/1/01	Sun 12/30/01
9	**LBES Validation**	**221 days**	**Mon 10/1/01**	**Tue 7/30/02**
10	Accessory Gearbox	221 days	Mon 10/1/01	Tue 7/30/02
11	Electrical Generator	221 days	Mon 10/1/01	Tue 7/30/02
12	**III. SHIPBOARD DATA ANALYSIS**	**199 days**	**Sat 12/1/01**	**Fri 8/30/02**
13	Install USS Fitzgerald (DDG-62)	199 days	Sat 12/1/01	Fri 8/30/02
14	Collect Information	66 days	Sat 12/1/01	Thu 2/28/02
15	Analyze Information	133 days	Fri 3/1/02	Fri 8/30/02
16	**IV. CLASSIFIERS, FUSION AND REASONING (SHM)**	**244 days**	**Mon 10/1/01**	**Fri 8/30/02**
17	Develop data fusion module for monitored components	244 days	Mon 10/1/01	Fri 8/30/02
18	Noncommensurate Data Fusion Study (Oil, AE with above)	155 days	Mon 10/1/01	Tue 4/30/02
19	**V. TECHNICAL REPORTS AND PROGRAM MANAGEMENT**	**265 days**	**Mon 10/1/01**	**Mon 9/30/02**
20	Report 12/01	1 day	Sat 12/1/01	Sat 12/1/01
21	Report 3/02	1 day	Fri 3/1/02	Fri 3/1/02
22	Report 6/02	1 day	Sun 6/2/02	Sun 6/2/02
23	Program Management	265 days	Mon 10/1/01	Mon 9/30/02



Future Naval Capabilities - Applications and Implementation

May 24, 2002

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INTRODUCTION

The following work is proposed under the Future Naval Capabilities (FNC) Initiative for FY02 through FY04 to validate and implement technologies demonstrated in the Accelerated Capabilities Initiative (ACI): Machinery Diagnostics and Prognostics Program. Since the hardware and software have been developed and demonstrated, the proposed tasks will enable the acquisition of performance data on diesel engines, accessory gearboxes, reduction gearboxes and electrical generators.

The Applied Research Laboratory has a number of active projects in the areas of reliability-centered maintenance, instrumentation, machinery diagnostics and prognostics. For example, the department is currently performing the Accelerated Capabilities Initiative: Machinery Diagnostics and Prognostics (ACI), sponsored by the Office of Naval Research (Dr. Thomas McKenna Code 342). The goal of this program is to develop a hierarchical architecture and demonstrate machinery health monitoring on a ships service gas turbine generator set (SSGTG). The generator set supplies electrical power to ship systems on board Arleigh Burke class destroyers.

The ACI project has produced a number of successful products. For example, the program has produced prototype hardware and software to implement machinery health monitoring and enabling prognostics and health management. The research team includes organizations for academia, industry and Navy. The ACI has completed hardware and software design with the development of various hardware solutions for the intelligent component health monitor. This hardware and software has been installed on the USS Fitzgerald (DDG-62).

The Future Naval Capabilities- Applications and Implementation is proposed to implement the developed technology for benefit to the Navy in several applications. The technology is currently in the process of being transitioned to the Advanced Amphibious Assault Vehicle (AAAV) Prognostics Program as part of the Total Ownership Cost FNC. This program will demonstrate machinery diagnostics technologies for the Power Transfer Module and Drivetrain components of the AAAV. With current interest in legacy and future ship platforms, this effort is proposed implement technology previously demonstrated by engineering change in cooperation with the Navy Surface Warfare Center Carderock Division – Philadelphia, as well as other platforms and technology areas such as oil analysis. Other applications of this technology can support the Electric Ship FNC in the areas of electrical motor performance and systems modeling.

Future integration and insertion of advanced condition-based maintenance technologies is now possible.

PROPOSED TASKS

I - MODULE IMPLEMENTATION

I.1 LBES FADC Design

The FADC module is to be upgraded for the Allison 501K and the GE LM2500 gas turbines. Implementation of the diagnostic technologies with the controller module would enable a rapid insertion of the technologies to the fleet with immediate impact. The FADC is based on an open

Windows architecture, enabling a hardware module for diagnostics to be designed as a plug-in module for the FADC, eliminating lengthy hardware approval cycles. This task will involve design of the module for compatibility with the FADC and a series of integration tests at LBES to qualify the design.

I.1.1 Design. A software Interface Control Document will be developed to provide diagnostics information to the FADC. This effort will be conducted in conjunction with NSWCCD Engineering personnel.
I.1.2. Hardware Integration. The module will be installed at LBES and tested for compatibility with the FADC.

I.2 FUSION OF GAS PATH AND VIBRATION DATA
ARL was requested by the USS Fitzgerald to include trend data for the 29 engine health values that are currently being displayed by the LOCOP. In addition, alert and alarm messages would be issued when these values fall outside of normal operating thresholds. This would also benefit the ACI program by facilitating research into how LOCOP data can be fused with vibration data to enhance real-time prognostic capabilities.

The approach will require an information fusion software scheme to combine information from ICAS, FADC or other sources with vibration data from machinery component monitors to effect fault isolation and enable fleet monitoring databases to develop relationships between the data and the health of the gas turbines.

II - ALGORITHM IMPLEMENTATION (to be conducted at Advanced Sensors and Control Evaluation Laboratory)
The successful demonstrations on the USS Fitzgerald and the USS Monterey have determined that the monitoring systems work on-board ships. However, implementation of the technology will require insertion for a class or classes of ships to be conducted. The Navy is currently pursuing a Gas Turbine Transition Plan for CBM that aims to focus the technology on DDG-class and CG-class vessels for the Allison 501K and GE LM2500 engines. Although the demonstrations determined threshold levels and provide preliminary data for analysis, a fundamental shortcoming in acquiring failure data still exists. While the current technology is sufficient for diagnostics, failure data is still necessary for implementation of prognostics.

The dynamics of components such as shafts, gears, and bearings are the primary concern. The mechanisms by which faults can initiate and how they evolve in these components can be characterized through an understanding of the unique set of signatures that each particular fault generates. Algorithmic techniques and data fusion approaches can be combined to increase diagnostic robustness and reduce false alarms. This is a key step towards developing a machinery prognostics capability that would enable abnormal conditions to be identified in their early stages of development, so that maintenance could be scheduled with minimum impact on operations. A limiting factor toward that end continues to be a lack of high fidelity data on how faults initiate and evolve.

A series of experiments on the unique test rigs is proposed.

II.1 High Speed Accessory Gearbox Test Rig (under construction)

This rig allows the accessory gearbox of the engine section of the Navy Allison 501-K17 and K34 SSGTG, to be operated at speeds approaching operating conditions to investigate vibration features for bearing and gear condition, including the effects of the fuel pump, lubrication pump, and other subassemblies. (See Figure 1.)

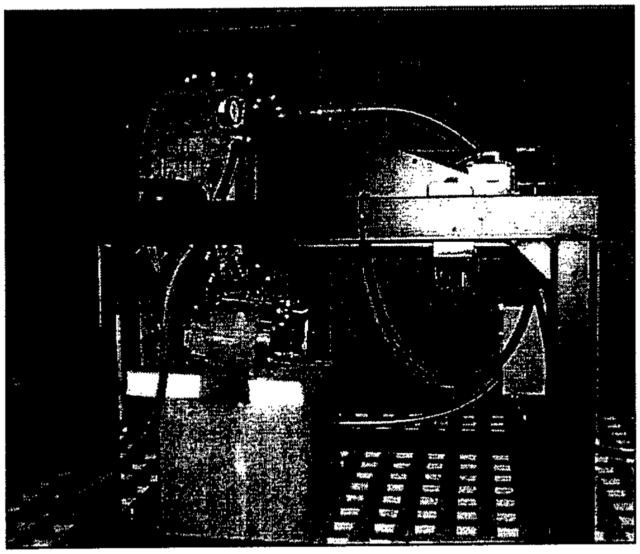

Figure 1. Under Construction - High Speed Accessory Gearbox Test Rig

1. Testing. (1) Evaluate the performance of various accessory gearbox bearings and gears to determine if replacing any of these components with state-of-the-art components could increase the life of the gearbox, since the Navy wants to extend the life of these gearboxes another twenty years. (2) Evaluate the performance of various bearing and gear algorithms developed under the ACI and MURI programs at PSU to identify algorithms suitable for running at LBES. Complete construction of the Accessory Gearbox test bed. This is estimated to take an additional three months, including testing in collaboration with NSWCCD.

2. Data Analysis. (1) Compare theoretical data developed at NSWCCD to the experimental data collected on the test rig. (2) Transition those algorithms that work reliably with good confidence will be transitioned to the LBES for inclusion into the FADC.

II.2 501K-34 Generator Test Rig

There are only two 501K electrical generator models in existence (One each at the University of Kentucky and ARL-Penn State). This test rig simulates the electrical generator section of the Navy Allison 501K-34 Ships Service Gas Turbine Generator, which is used aboard the DDG-class destroyers. The rig enables faults in the windings, diodes, and rectifier assemblies to be seeded into the machine while monitoring electrical voltages and currents along with mechanical vibration. (See Figure 2.)

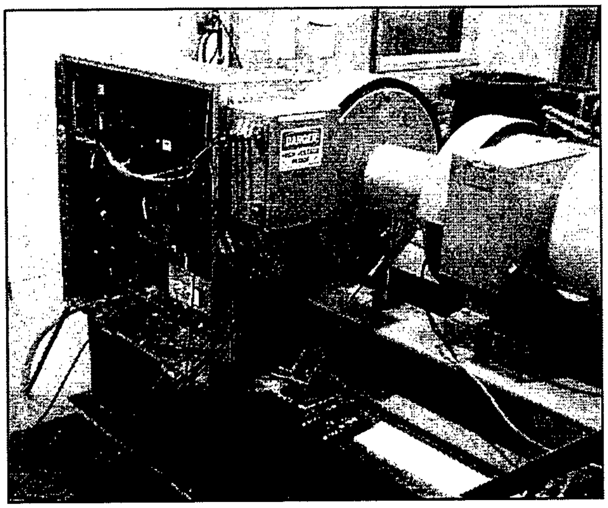

Figure 2. 501K-34 Generator Test Rig

Generator Testing. One final test needs to be completed using a seeded fault in a bearing. Both electrical and vibration data will be collected to determine what effects a failing bearing has on the electrical signatures of a generator. The University of Kentucky and Rensselaer Polytechnic Institute will support ARL in assessing the performance of the algorithms and investigate classifiers, fusion, and reasoning at the system level.

II.3 Oil Analysis and Vibration Analysis

Historically vibration analysis has been the technique for monitoring the condition of large, critical pieces of rotating equipment. Conversely, oil analysis has been used to make effective maintenance decisions. Traditionally, both vibration and oil analysis has been used independently from one another for monitoring the health of rotating machinery. Since then, however, it has become evident that an integrated approach to machine health monitoring yields a higher degree of success. This discussion has taken on popularity over the past several years and is being echoed throughout both the oil analysis industries and the vibration industries through trade magazines, seminars and conferences.

Many off-line, spectroscopic and morphological techniques exist to analyze lubricant condition and wear metal debris. The employ of such off-line methods is inconvenient and increases the labor maintenance cost and workload associated with operation of the platform. Over the past decade many on-line techniques have also been proposed. Inductive oil debris monitors are useful for the characterization of both ferrous and non-ferrous particulate and have high detection efficiencies for metallic particles greater than 150-175 microns and nonmetallic greater than 350 microns. Adding particle morphology (size, shape and curvature) capability in on-line systems can contribute to early detection and avoidance of catastrophic conditions, especially in critical applications such as engines and gearboxes for helicopters.

In general, many researchers are reaching the similar conclusions about combining oil analysis and vibration analysis; they are powerful tools that need to be combined to better assess machine condition. The focus of work should address methods that can be used to combine the techniques and define data fusion approaches that may increase diagnosibility and reduce false alarms. Often one type of analysis tends to be a strong and early indicator of the existence of machine failure while the other triggers later as the confirming indicator. There are instances also where one technique indicates a fault while the other shows no change. Examples can be seen in **Table 1**.

Problems/Conditions	**Oil Analysis**	**Vibration Analysis**	**Correlation**
Thrust/Journal/Roller Bearing	Strength	Mixed	Wear debris will generate in the oil prior to a rub or looseness condition
Misalignment	Not applicable	Strength	Vibration program can detect a misalignment condition. Lube analysis will eventually see the effect of increased/ improper bearing load.
Oil Lubricated Antifriction Bearings	Strength	Strength	Lube program will detect / can detect an infant failure condition. Vibration provides strong late failure state information.
Shaft Cracks	Not applicable	Strength	Vibration analysis can be very effective in monitoring a cracked shaft.
Gear Wear	Strength	Strength	Vibration techniques can predict which gear. Lube analysis can predict the type of failure mode.
Root Cause Analysis	Strength	Strength	Best when both programs work together.

Table 1. Partnering Oil with Vibration Analysis

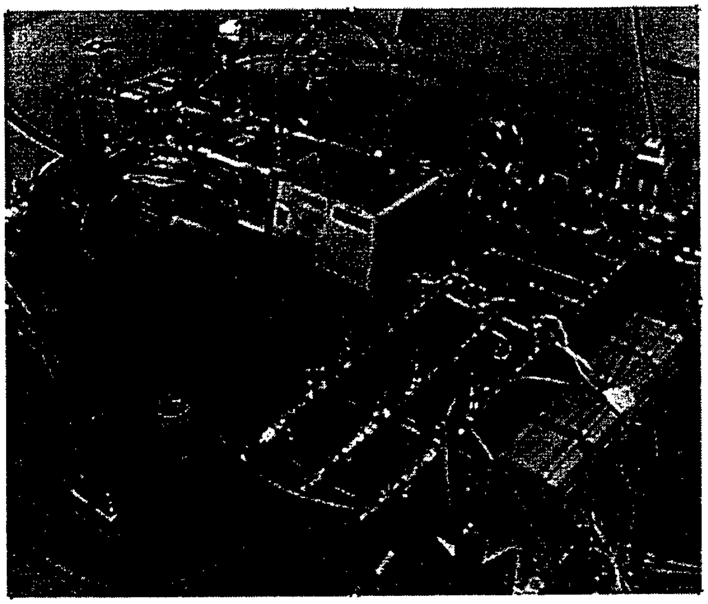

Figure 3 – Lubrication Test Bench

The lubrication system can possess many types of fault effects that are coupled with the functioning of the oil system as well its related (oil-wetted) components. A common focus for oil analysis is on the production of wear debris in its wetted components. This occurs during initial break-in wear, stable wear over component life with some degree of dynamic equilibrium, and in some cases, abnormal wear due to component damage or lubricant failure. Common wear mechanisms include pitting fatigue of gears or bearings, abrasion, scuffing corrosion and fretting wear. When solid contamination of the lubricant occurs, the result is what is often referred to as "three-body abrasion wear". This problem is of particular concern in higher performance applications where the high-hardness gear wear may provide the third body that causes significant secondary wear in bearings. Table 2 lists many of the failure mechanisms that may occur in oil-wetted components.

Gear Faults	Bearing Faults
Plastic Deformation	Surface Wiping
Pitting	Fatigue
Heavy Scuffing	Fretting
Chipping and Tooth Crack	Foreign Debris
Tooth Breakage	Spalling
Case Cracking	Inadequate Oil Film
Surface Fatigue	Overheating
Abrasive Wear	Corrosion
Chemical Wear	Cavitation Erosion

Table 2. Wetted Component Faults

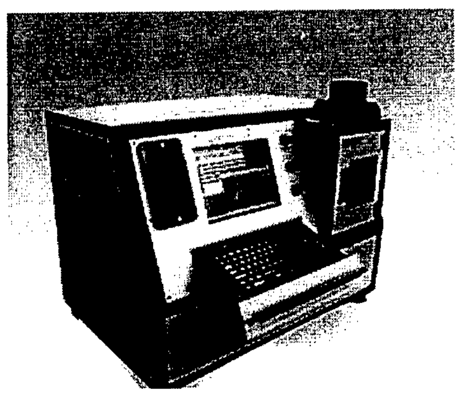

Figure 4 – Oil Analysis Spectrometer

The Spectroil Spectrometer will be used to assess and evaluate oil sensors for specific applications of interest to the Navy and DOD community.

CONCEPT DEVELOPMENT FOR FUTURE PLATFORMS

This task is to provide support to conduct data acquisition on opportunistic basis for new platforms. This data collection will be conducted at Navy or approved contractor facilities. This task will also support conceptual design of machinery monitoring systems for new platforms. Potential applications of this task will be to support new platforms such as DD-X and also electric-ship power machinery systems such as electrical motors, generators and power supply and distribution.

Another important opportunity is in Ship's Service Diesel Generator (SSDG) Diagnostics and Prognostics. Opportunities exist in future programs to gather and analyze data on a new family of SSDGs aboard the Navy FFG-7 class ships. In conjunction with the diesel OEM (Caterpillar), a fully instrumented diagnostics/prognostics suite is proposed for over 100 new 3512B engines.

PROGRAM MANAGEMENT - TECHNICAL SUPPORT

(1) Support to disseminate and educate the research community regarding the application of diagnostics to legacy and future platforms.
(2) Support for the Office of Naval Research in management of programs for Condition Based Maintenance and Total Ownership Cost Reduction.

RELATED EFFORTS/BENEFITS

Completion of this effort would benefit the proposed Navy Gas Turbine Transition Plan as well as a proposed DARPA program in Asset Readiness. The Navy transition plan includes the upgrading of the FADC for the Allison 501-K series and the GE LM2500 engines. These engines comprise a large part of the Navy's installed base for shipboard electrical power generation and propulsion. This proposed effort offers the opportunity to exercise the capabilities of the Advanced Sensors and Control Evaluation Laboratory awarded under the Defense University Research Instrumentation Program (DURIP). This award has supplemented ARL's capabilities with precision instrumentation for oil analysis and sensor validation.

RESEARCH TEAM

The research team consists of current ACI Team Members. NSWCCD will provide LBES facilities and assist in design. GE and Allison will provide technical support to the team. The University of Kentucky, Rensselaer Polytechnic Institute, and ARL-Penn State will refine the performance of the algorithms and investigate classifiers, fusion, and reasoning for the system level.

Other (potential) members of the research team could include: Caterpillar; Lockheed-Martin; Naval Research Laboratory; to name a few.

BUDGET

Estimates for the proposed effort (FY02-04) are as follows:

Team Member	**02**	**03**		
NSWCCD (and subs) estimate	$ -	$ 150,000		
PSU ARL	$ 92,297	$ 767,263		
RPI	-	$ 75,000		
U of Kentucky	-	$ 60,080		
Vector Technologies	$ 269,600	$ 281,000		
Total PSU ARL Funding:	$ 361,897	$1,183,343	**Total PSU:**	**$1,545,240**
Total Team Funding (est.):	$ 361,897	$1,333,343	Total Team (est.):	$1,695,240

SCHEDULE (6/02-9/03)
Applications and Implementation

SCHEDULE	FY02 3QTR	4QTR	FY03 1QTR	2QTR	3QTR	4QTR	FY04 1QTR	2 QTR	3QTR
I. MODULE IMPLEMENTATION									
I. 1 FADC Design									
Circuit Board Design			∇						
Board Fabrication			∇						
Integration and Installation at LBES			∇—∇						
Engineering Change Proposal			∇	—	—	—	∇		
I.2 Fusion of Gas Path and Vibration Data									
Data Fusion Algorithms on Gas Turbines Engines			∇	—	—	—	∇		
II. ALGORITHM IMPLEMENTATION									
II.1 High Speed Accessory Gearbox Test Rig			∇	—	—	—	∇		
II.2 Generator Test Rig			∇	—	—	—	∇		
II.3 Oil and Vibration Analysis			∇	—	—	—	∇		
III. CONCEPT DEVELOPMENT FOR FUTURE PLATFORMS									
Site Survey and Data Collection			∇	—	—	—	∇		
IV. PROGRAM MANAGEMENT									
Meetings and Reports	∇	—	—	—	—	—	∇		