Health Management for In-Service Gas Turbine Engines

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Agenda

- Legacy Maintenance
- Implementing Health Management
- Choosing the Project
- Enabling Technologies
- Health Management & Prognosis Process
- Validation/Verification and Transition Planning
- Conclusions

Legacy Maintenance

- Re-active to faults
- False removals
- Unplanned events
- Fixed maintenance & inspection schedules based on fleet wide statistics
- Limited predictive capability

Legacy Systems Drive Increasing O&S Costs

Implementing Engine Health Management

Objectives:

- Provide continuous, accurate assessment of engine health
- Reduce or eliminate inspection tasks
- Improve mission planning capability
- Enhance prognostic capability

Health Management for In-service and New Engine Programs

In-Service Programs

- Large installed base
- High operating tempo
- High and growing O&S costs
- Little opportunity to upgrade

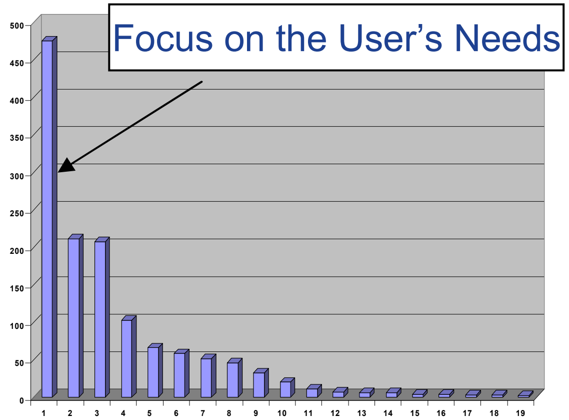
New Product Development Programs

- Advanced control systems
- Competitive marketplace
- Technology insertion potential

Health Management Technology –Adaptable to Meet Customer Needs

Choose the Right Project

- Focus on User's needs
  - Clear impact on metrics
- People adapt to current methods
  - Often unable to perceive a problem
- Replace margin with knowledge
  - Individual health vs. fleet averages
- Pick the right team – diversity
  - Cross functional team…
- Define success
  - Small, early wins are important
- Plan transition and implementation – upfront
  - Think through all the steps



Select those issues that can significantly impact operational metrics

System Solution to User Needs

NOT:

- Technical specialty
- IT project
- AI/Reasoning project
- Applied statistics project
- Sensor or control system design
- Marketing

Apply the right technologies to achieve a system solution

System Solution To User Needs

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Enabling Technologies

- Continuous on-board data recording
- Advanced algorithms/models
- Multi-purpose PC-based ground stations
- Open architectures
- High speed data transfer
- Data warehousing
- Digital architecture
- Diagnostic instrumentation

<u>Dynamic view of technology</u>

Avoid reasoning that something will never be possible because all previous attempts have failed

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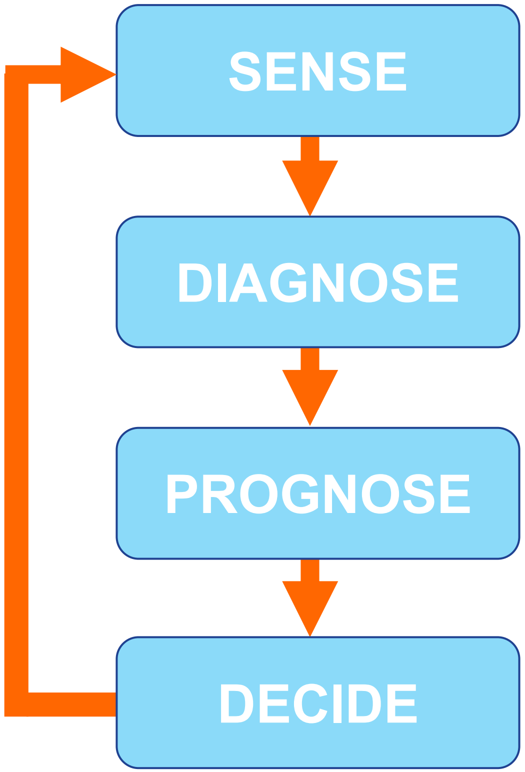
Health Management and Prognosis Process



Establish state awareness via engine and aircraft sensors and systems

Determine the ability of a component to perform its function. Detect and isolate faults with a high degree of accuracy and a very low false alarm rate.

Predict remaining useful life. Use the current state and state transition vectors to model fault progression

Engine control system, aircrew, maintenance, mission planning, logistics, depot, etc.

Sensing

- Evaluate capability with the existing sensor set
  - Leverage sensors used for other purposes – with caution
- Models can help
  - Models can expand the sensor set via 'virtual sensors'
- Consider retrofit issues when evaluating new/additional sensors
  - Cost/weight/reliability
  - Interface requirements
- Demand that new sensors buy their way on

Measurement	**Cost**	**Benefit**
Valve open/closed	$	70%
Valve position (% open)	$$	90%
Flow measurement	$$$$	98%

Data Challenges and Solutions

- Data accuracy and bias
- Outliers and outlier rejection logic
- Noise and filtering logic
- Data frequency
- Data stability
- Gaps and missing data
- Digitization
- Data errors –Intermittent and noisy signals

•Analysis of real field data

•Error detection and correction algorithms

•Improved fault detection, accommodation and isolation

•Reduced S/N ratio

•Data selection/rejection criteria

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Diagnostics

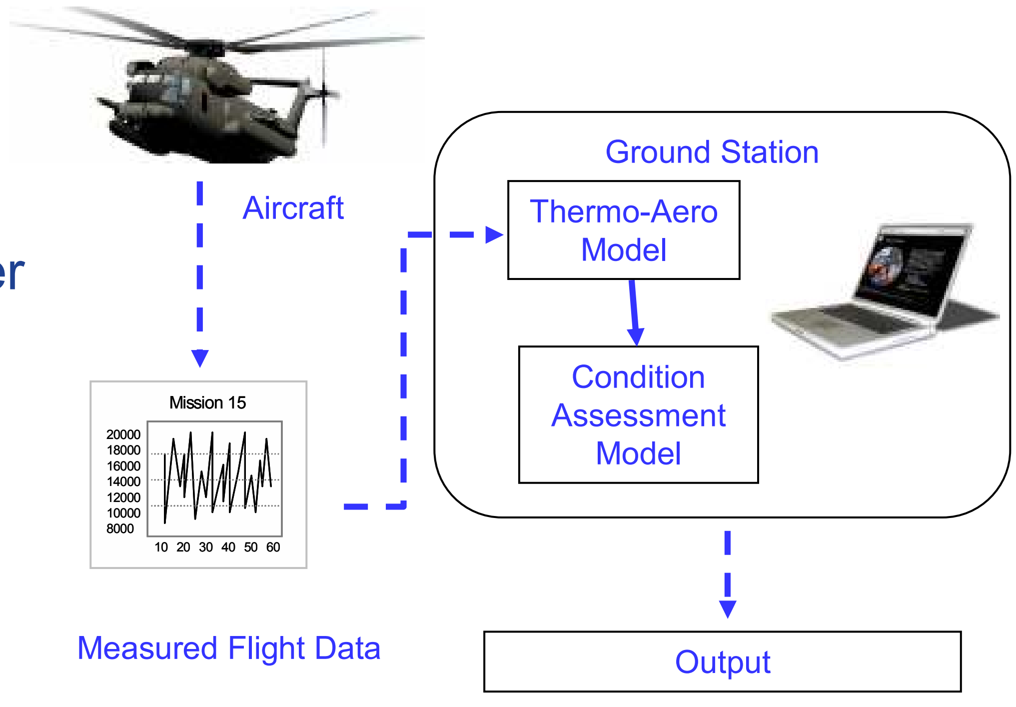
- Understanding the underlying process allows the condition to be assessed
- Know when diagnosis is possible
  - Aeromechanical and thermodynamic stability
  - Stable enough?
- Fix the problem vs. monitoring its health
- False positives and false negatives
  - Evaluate the rate & consequences

Fault Testing

- Real faults vs. test inserted faults
  - Real faults are more complex
  - Examine what really happens – field experience
  - Hindsight bias: judging past events as being clearly predictable
  - Relying on testing and results that confirm hypothesis and downplaying contradictory findings
    - » Need for independent outside reviews

Models

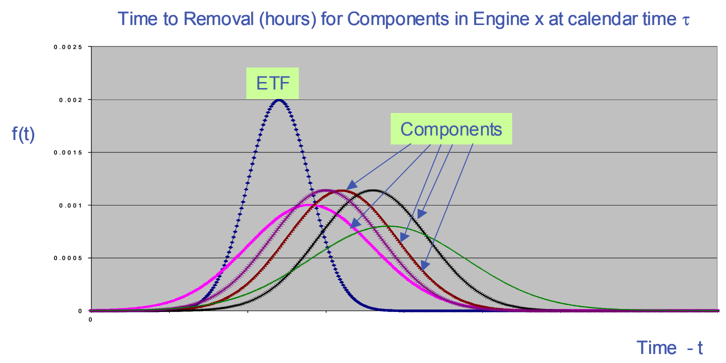
- Models are based on an interpretation of a physical system
  - Models are often insufficiently robust to cover real world conditions
- Deployed model robustness must address
  - Field usage
  - Installation effects
  - Operating conditions
  - Environmental conditions
  - Failure conditions
- Model size and timing
  - Impact on other systems



Despite all the data and models, experts can often determine when something is wrong and intervene based on experience – it not all data

Prognosis

- Prognosis models evaluate and combine usage accumulation to predict the part, subsystem and engine reaching its usable life
- Determines the probability of each component being the first to force engine maintenance or removal
- Determines the expected (average) time when engine will be removed and its uncertainty given the current distributions (forecasts) of individual removal times



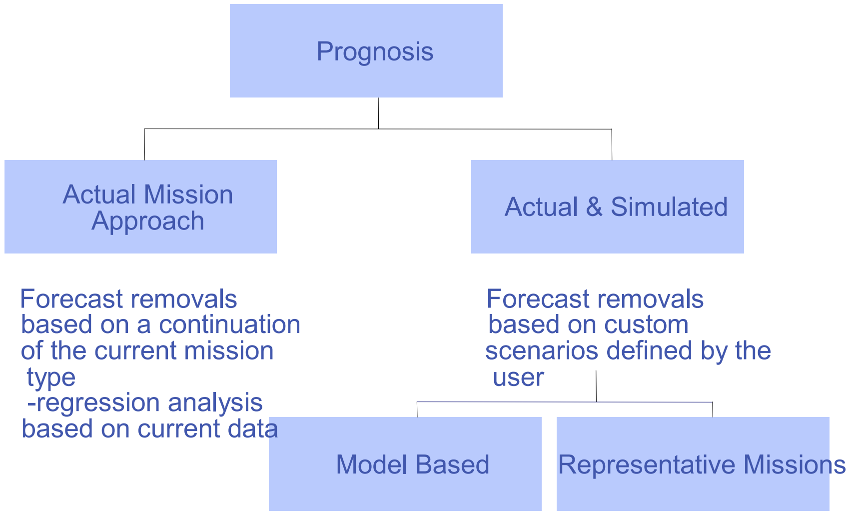
Probability and RUL is Recalculated After Each Flight

Prognosis Output

- Fleet Management
  - Survivorship plots
  - Percent of parts reaching a limit as a function of operating time
- Local Unit/Logistics
  - Removal Time Prediction
  - Estimate of time remaining based on planned usage
- Depot/Service Shop
  - ‘No Build’ Window
  - Probabilistic assessment of part replacements needed for desired ‘no-build’ window

Prognosis

- Prognosis tool development focused on needs of end user
- Need for continuous data to develop prognosis models
- Component-specific prognosis and total engine prognosis (engine performance + component life)
- Prognosis based upon actual mission data or upon mission simulations



Model cause of condition change
- Internal or External
- Usage is individualized
- Adaptation and learning

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Decisions

- Engine control system
  - Optimize engine operation
- Aircrew
  - Critical information on system
- Maintenance
  - Unambiguous information
- Mission Planning
  - Engine specific knowledge
- Logistics
  - Lean support
- Service Shop
  - Optimal build windows

Data Management

- Data storage
  - Memory is inexpensive, retrieval can be expensive
  - Linking or indexing data is key
- Data reprocessing
  - Is it necessary?
- Data Mining
  - Learning by mining the existing databases

Validation/Verification and Transition

- Efficacy/Accuracy
  - Demonstrate that the health management program meets program goals
  - Assess accuracy and uncertainty
  - Demonstrate prognosis algorithms accuracy
- Integration and functionality
  - Demonstrate functionality in the target environment
- Safety
  - Evaluate safety risk compared to baseline system

Summary

- Health management can be applied to in-service products
  - Control escalating operating and support costs
- Use care when selecting the project
  - Focus on users needs
  - Plan transition and implementation upfront
- Manage the project as a health management solution
  - Use all necessary technologies but don't lose site of the end goal
- Leverage enabling technologies
- Evaluate all proposed increases in sensors/systems
- Design for real data and real systems
- Understand the decisions that will be made from these systems
- Transition to target environments

Thank You