Propulsion Safety and Affordable Readiness Engine
Health Management Plan

Brian K. Beachkofski
AFRL/PRTS
US Air Force Research Laboratory
1950 Fifth Street
Wright-Patterson Air Force Base
OH 45433, USA
937.255.7219
brian.beachkofski@wpafb.af.mil

Abstract—A new initiative was started to address Department of Defense safety and affordable readiness for legacy turbine engines. By using the GOTChA/ApPRoVal methods, a baseline research plan was established that is based on prognostics and health management. This paper outlines the decision process, investment strategy, projected return on investment, validation, and transition strategies.

1. INTRODUCTION

The Air Force Research Laboratory (AFRL) has recently changed the method in which it decides its long term investment strategy. The new process, called Focused Long Term Challenges (FLTC), aligns the research targets and the technology needs to realize the operational requirements of the Air Force in 2025.

One of the identified challenges is to assure that affordable reliability and readiness exists in whatever shape the future fleet takes twenty years hence. A primary path to achieving that affordable readiness is by using Prognostics and Health Management (PHM) technologies. While these plans include the entire weapon system, in the Turbine Engine division we are orchestrating the Engine Health Management (EHM) plan as part of the Versatile Affordable Advanced Turbine Engine (VAATE) Program.

The plan was developed using the process outlined in [1] to transition technology programs that meet user needs in a timely manner. This paper outlines the application of that process to the EHM plan as developed within the Propulsion Safety and Affordable Readiness (P-SAR) initiative.

The P-SAR initiative is made up of representatives from each of three services (Air Force, Army, and Navy) and NASA. The representatives identified their service requirements and made technology-based teams in which to develop the research plans.

The initiative derived safety and affordable readiness goals from Department of Defense (DoD) guidance. Secretary Rumsfeld’s long-term safety goal of “zero preventable mishaps” [2] led to the safety goal of reducing propulsion related Class A mishaps ($1M in damage or loss of life or aircraft) by 75%. There is a similar drive to address growing sustainment costs. The affordability goal is to maintain the required war readiness while reducing those expenses by $420M annually.

The initiative is designed to demonstrate the required technologies to a Technology Readiness Level 6 (TRL-6) by 2013. Transition and implementation of technologies will begin as soon as a given approach reaches TRL-6, but will continue after the 2013 timeframe.

The transition plan is important and put together by its own sub-team. They validate that the objectives are met and that the system is ready for implementation.

2. DEVELOPMENT TEAM

A team of Army, Navy, Air Force, and NASA representatives developed the initial technical plan with input from the propulsion Original Equipment Manufacturers (OEM). The objective of the team was to initially bring the government personnel who have complete fleet wide visibility together with the industry partners who

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1 U.S. Government work not protected by U.S. copyright.
2 IEEEAC paper #1219, Version 2, Updated January 3, 2005
have expertise in the specific systems. As the process matures, the team will grow to include other industry partners outside of the OEM and university researchers.

The government team members represent each service and NASA each bringing their own vision for the future. The Air Force is most interested in extended the hot time that the engine is designed for, responding to their requirement of greater thrust and longer operation times. The Army, who flies a majority of their missions close to ground level, focuses on life extension in the presence of sand and particulate ingestion. Without a secondary runway or convenient bail-out area, the Navy is determined to drive system reliability as high as possible through an engine-wide prognostic health capability.

The engine OEM input typically stemmed from their planned Internal Research and Development (IR&D) or company research center progress. The companies have invested in those technologies because they match their business direction and are interested in seeing that investment become a formal program.

Much like the major OEM, smaller industry partners and academics have their research path that they want to be developed and transitioned to an operational system. Because of the lack of direct control of the transition path and the number of companies, inclusion in the initial plan is difficult. The approach taken is to incorporate technology feeders in follow-on plans.

The development team must balance each representative’s parochial goal for the benefit of the entire initiative. By allowing the service with the greatest interest in a particular area to lead that area, the best plan for each of the sub-areas will be formed. That, in turn, will make the best overall plan for the entire group.

3. REQUIREMENTS

The safety requirement stems from a recent push in the Depart of Defense, the ultimate definier of military requirements. The long-term goal of “zero preventable mishaps” [2] is planned to be implemented through better systems engineering in the acquisition process. A memo from the Undersecretary of Defense states “Our intent is to design safety into our weapons systems, not add it afterwards as an operational consideration” [3]. A technology program is required to give the acquisition community the option to include advance safety technologies into their systems. Safety has also been included in the new DoD Directive 5000.1: “Safety shall be addressed throughout the acquisition process…managed through the application of a systems engineering approach” [4].

Figure 1. Process Flow Diagram.

Directive 5000.1 also states that system acquisition should minimize total ownership costs [4]. Based on current data, the US Air Force spends $2.87B annually in non-fuel engine sustainment. The total DoD expenditures in non-fuel engine sustainment are $4.17B. This is a significant opportunity, or as Dr. Sambur (Assistant Secretary of the Air Force for Acquisition) said, a “train-wreck” if our processes within the Air Force don’t change to address growing costs [5]. Modernization dollars are being diverted to address sustainment costs, which causes the fleet to age and require more funds to sustain. This cycle is what Dr. Sambur calls the “burning platform,” referring to a North Sea oil drill where a small fire was allowed to burn until it grew to be uncontrollable and had to be abandoned. We cannot ignore technology solutions to sustainment costs until the problem grows out of control.

4. GOTCHA PROCESS

The GOTChA process is a method to translate requirements into technical approaches to build a program. The entry point into the process is the DoD requirement. The steps are to establish goals for the initiative, to create technical objectives, to identify technical challenges, and to list approaches to overcome those challenges. The result is a list of approaches, which successfully complete, would meet the user requirements. This section describes how that translation took place for the P-SAR initiative.
Goals

The Senior Advisory Group (SAG), principally comprised of the propulsion directors from each service and NASA, established the goals for the initiative. They did this by reviewing the current situation as depicted in Section 3 and determining what impact a technology program within turbo-propulsion could accomplish.

The P-SAR initiative set the safety goal as a 75% reduction in the number of propulsion related Class-A mishaps ($1M in damage or loss of life or aircraft). The affordable readiness goal is to maintain the required war readiness while reducing those expenses by $420M annually. An ancillary goal was created to help reach the affordability goal; since it is known that TOW and cost per engine flight hour are closely connected [6], doubling current Time on Wing (TOW) was also included.

These goals guide the effort and provide the benefits that can be directly linked to DoD policy, official memoranda, and directives. Though traditionally the requirements would come from an Initial Capabilities Document (ICD), grounding the goals to published memoranda and directives provides that same formal establishment of requirements.

Objectives

The second step in the process is to create technical objectives from the goals. To do this, the link between the system engineering and the goals needs to be established. In other words, the team must answer question, “Why can’t we currently design an affordable, highly available system without failures?”

The answers depend on individual failure modes within an engine and also vary with differing usage between the services. The SAG tasked each service to perform a study looking at the major safety and cost drivers based on safety center and maintenance cost data. The study showed which components had reliability concerns and drove preventive maintenance, inspections, or safety incidents.

Based on the results of the tri-service deep look study, the team was broken into several sub-teams: hot section, compression section, power, prognostics and health management, materials, and bearings/mechanical systems. Each team was responsible for identifying the objectives in their component area. The sub-team lead was selected from the service with the most interest in each component area. They were the most familiar with the exact risk mode or cost driver and had the most to gain from a successful plan.

The objective is not expressed as simply as a component reliability, but explicitly ties into a documented failure mode or addresses a technical order put in place as a risk mitigation measure. For example, turbine reliability may be driven by Thermal Barrier Coating (TBC) integrity, so the objective could be to identify a TBC spall less than 0.25cm² in area.

These objects must be quantifiable so that validation testing can determine the success of the program. They must also be defined correctly so that meeting the objectives implies that a system that meets the goals is available.

Technical Challenges

The objectives are currently unachievable because of existing technical shortfalls. If we continue the TBC spallation example, the spall cannot be detected because of poor infrared optical resolution in operational conditions. That is an example of a technical challenge. There can be several challenges for each objective. Another challenge would be detecting TBC spallation through exhaust gas spectroscopy due to the small mass fraction of the identifying elements in the exhaust as a whole.

In addition to the legacy data, the teams also identified pipeline and future systems that, because of new design or manufacturing processes, have risk elements unlike prior generation systems. The P-SAR list of challenges includes these emerging issues.

Some overlap in technical challenges across multiple groups is to be expected. An instance of this would be blade tip timing of arrival sensing which plays into both compression and turbine sections. The SAG recommended an additional team called the Integration, Transition, and Implementation (IT&I) team that would integrate the component level plans into a single, cohesive, and non-duplicative research strategy.

Approaches

After identifying the objectives for their component area, each sub-team lead polled their group to identify research approaches that could overcome the challenges. Specifically, each service representative collected their respective plans for that area including input from the OEM. The representatives met in June 2005 and combined approaches into a complete list.

This list includes effort that are external contracts (both ongoing and programmed), in-house research (government and IR&D), and unfunded plans. The catalog of approaches was left unrestricted by funding realities and the schedule was set to meet the program goals by the 2013 end date. The recommended technical approaches were presented to the SAG at a review meeting held in July 2005.

The approaches are classified into three major groups. The first group is the materials and manufacturing technologies. The second major class is the component design and analysis team. The final group is the prognostic and health management team that integrates the material models and stress analysis with sensor and reasoning technologies to track life usage.

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The actual results, including safety incidents, root causes, and maintenance costs by component are not included because of public release requirements.
The direction from the SAG was to execute the best program using available funding and choosing approaches from the proposed list. Specific recommendations to create demonstration plans with exit criteria that can be used to validate the technologies. A special area of emphasis is implementation and transition, which the IT&I team coordinates.

5. ApproVal Process

The recommendations from the SAG were, in essence, to complete the AppRoVal process. They suggested using the prioritization of the technical challenges, based on expected benefit, to create a plan. Following that, they directed the team to roadmap the plan to align demonstration opportunities and create exit criteria that define the validation procedure.

Priorities

Risk analysis methods have used risk and consequence analysis to determine risk mitigation strategy for a system. One instance of its use is in reliability-centered maintenance, where Failure Modes Effects and Criticality Analysis (FMECA) aids decision making. The probability of occurrence and system impact of that occurrence feeds the build policy decisions.

When prioritizing programs, a similar tactic can aid in ranking the approaches. Rather than assessing the expected damage (probability of damage times amount of damage) we look at the expected benefit.

The expected benefit can be defined as the probability of successfully meeting the technical objects multiplied by the effect that objective has towards the goals. This is standard expected value analysis [7] and is expressed mathematically for discrete variables as

\[ E[f(x)] = \sum_x f(x)P(x) \]  

where \( E[\cdot] \) is the expected value, \( P(x) \) is the probability of event \( x \), and \( f(x) \) is the benefit value of that event.

The analysis can also be done in tabular format by using only relative probabilities and benefits. Such a table is shown as an example in Figure 1.

In this representation the colors denote the expected benefit: green is high, yellow is medium, and red is low. The color is an arbitrary assignment and some shifts could be made, especially in the center. The important information is that upper-right is better than upper-left or lower-right. However, both of those areas are better than lower-left.

The prioritization step is linked back to the technical challenges. Those challenges that are more likely to benefit the system will be selected to proceed, while challenges that are less likely to benefit the program will be delayed or not executed.

![Probability of Success](image)

<table>
<thead>
<tr>
<th>Objective Benefit</th>
<th>H</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Success</td>
<td>H</td>
<td>M</td>
<td>L</td>
</tr>
</tbody>
</table>

Figure 2. Expected Benefit Matrix.

Roadmap

The relatively higher priority programs are matched to available funding so the expected benefit of funded program is the highest possible value. These funded programs for the initial research agenda and are put into the roadmap format.

The roadmap has several elements, the first being the program timeframe. The funding years and schedule need to be put together. Some programs depend on each other and their schedules must be worked out so the timing will work.

The major schedule coordination tasks are the demonstration steps. Demonstration opportunities are expensive elements of the development process and aligning multiple technology demonstrations on the same test platform apportions the cost over several programs.

To ensure that the test plan correctly plans and utilizes demonstration opportunities, exit criteria have to be written for each TRL demonstration. The criteria need to be clear, measurable, and tied to the objectives.

Clear success criteria early in the development process present unambiguous expectations for the contract implementation. It also allows for other projects to know what will be produced in a separate effort. When the criteria are linked to the objectives, successfully meeting the exit criteria also means that the objectives are met.

The final step in roadmapping is to match technology availability to platform transition windows. If there is not a transition opportunity at the scheduled validation date the benefit of the program will not be realized. The transition platform also helps define how the system needs to be designed. A bearing health management system designed for a high-speed spool will be different that for a bearing within a gearbox.
**Validation**

Cost and safety goals are very hard to validate in a single engine test. Often initial estimates can be made from analytical or statistical models. The analytic models depend on the assumptions that go into it which are often unreliable or are not accurate projections of future operations. Statistical or empirical models depend on relevant data which is not available at the beginning of system deployment.

Reliability and safety data cannot be validated in a single test because a single test is unable to capture the variation in operation. A margin test is close, but may not accurately reflect conditions that lead to failure.

Likewise, cost projection is generally accurate in trend but not in magnitude. To validate that the cost goal is met, part consumption or overhaul schedules must change. It takes several years to consume an overhaul interval or have sufficient part consumption data to see a significant difference between two processes. Validation must therefore be an ongoing effort accomplished by updating Weibull statistics and cost data during Field Service Evaluations and early operations.

**6. IMPLEMENTATION & TRANSITION**

The perfect system would not fulfill the goals if it was never put into operation. To meet the customer requirements, the loop must be closed by having an implementation plan and ensuring that it is funded and executed. The necessary conditions for transition vary for different systems and need to be tailored to the exact needs.

A life prediction tool or failure progression model may be relatively easy to transition through a component analysis to reassess reliability. If that same model were applied in real-time as a life usage calculation forming the basis of scheduling maintenance then transition may be more difficult. Issues like data availability, on-board computing power, and risk become more important.

Adding a health management system to an engine inherently makes the system more complex and may lessen reliability if the system is not robust. That breeds a natural reluctance from engine managers to depend on a new, unproven technology. The answer is to have system implementation and transition woven into the development process to lower risk to the system at transition.

The engine managers should also be included in the development process and technology reviews. In P-SAR there is the IT&I team that works directly with a service customer coordination team. The service customer coordination team is comprised of the engine managers from each of the services and reviews the technology development to verify they are applicable and will contribute to the goals.

Further, there is an industry advisory panel that concurs that the P-SAR plan is in accordance with the OEM Engine Life Management Plans (ELMP). These review teams coordinate the stakeholders’ requirements and transition paths for the initiative.

**7. FUTURE**

The current P-SAR research plan does not extend out to 2013 because future funding levels, transition opportunities, and technology availabilities are unknown. The plan will evolve and respond to needs as it grows. There is a great opportunity based on the initial plan and the structure in place to adapt.

As the plan grows and future research opportunities become available the academic and vendor communities will help comprise the technology team. They bring a special ability to bring more approaches to a technical problem purely because of their numbers and desire to differentiate themselves from other researchers. Because of that, they may bring solutions to research issues with which the OEM has difficulty.

Focusing on solutions and using the GOTChA/ApPRoVal process implemented in a formal initiative structure will allow the team to accomplish the initiative’s goals. The formalized transition and implementation process implies that the DoD requirements of considering life cycle cost and safety in the acquisition cycle occur.

**REFERENCES**


BIOGRAPHY

Brian Beachkofski is a distinguished graduate of the US Air Force Academy class of 1998 where he earned his BS in Engineering Mechanics. He followed that by earning his MS in aerospace engineering at Georgia Tech, graduating in 1999. His PhD in Mechanical Engineering from Wright State University was completed in 2004, focusing on probabilistic analysis methods to reduced confidence intervals. He is currently with the Air Force Research Laboratory's Turbine Engine Division as the engine health management lead.