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NASA Aviation Safety Program Aircraft Engine Health Management Data Mining Tools Roadmap

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ABSTRACT

Aircraft Engine Health Management Data Mining Tools is a project led by NASA Glenn Research Center in support of the NASA Aviation Safety Program's Aviation System Monitoring and Modeling Thrust. The objective of the Glenn-led effort is to develop enhanced aircraft engine health management prognostic and diagnostic methods through the application of data mining technologies to operational data and maintenance records. This will lead to the improved safety of air transportation, optimized scheduling of engine maintenance, and optimization of engine usage. This paper presents a roadmap for achieving these goals.

Keywords: NASA Aviation Safety Program, Data Mining, Engine Maintenance

1. INTRODUCTION

The United States set a national goal in 1997 to reduce the fatal accident rate for aviation by 80% within ten years. The Aviation Safety Program (AvSP) was created as NASA's response to this goal (figure 1). The technology objective of the AvSP is to "reduce the aircraft accident rate by a factor of five within 10 years (by 2007), and by a factor of 10 within 25 years (by 2022)[1]." The AvSP officially started in late 1999. It is a five-year program whose aim is to perform research and develop technologies that will support the achievement of the national goal and lay the groundwork for NASA's more aggressive 25-year objective. Figure 2 depicts the structure of the NASA AvSP, the management umbrella above the various projects or thrusts.

One of the research areas under AvSP is Aviation System Monitoring and Modeling (ASMM). This effort is led by NASA Ames Research Center. The intended outcome of ASMM is world-wide aviation monitoring allowing continuous insight and assessment of system health and operations. ASMM is focussed on the development of tools and techniques to access and analyze onboard and system-wide aviation information in order to realize operational safety improvements. Figure 3 shows the project structure under the ASMM area, which includes a task called Data Analysis Tools & Intramural Monitoring. It is under this task that the NASA Glenn-led effort, referred to here as Aircraft Engine Health Management Data Mining Tools, resides.

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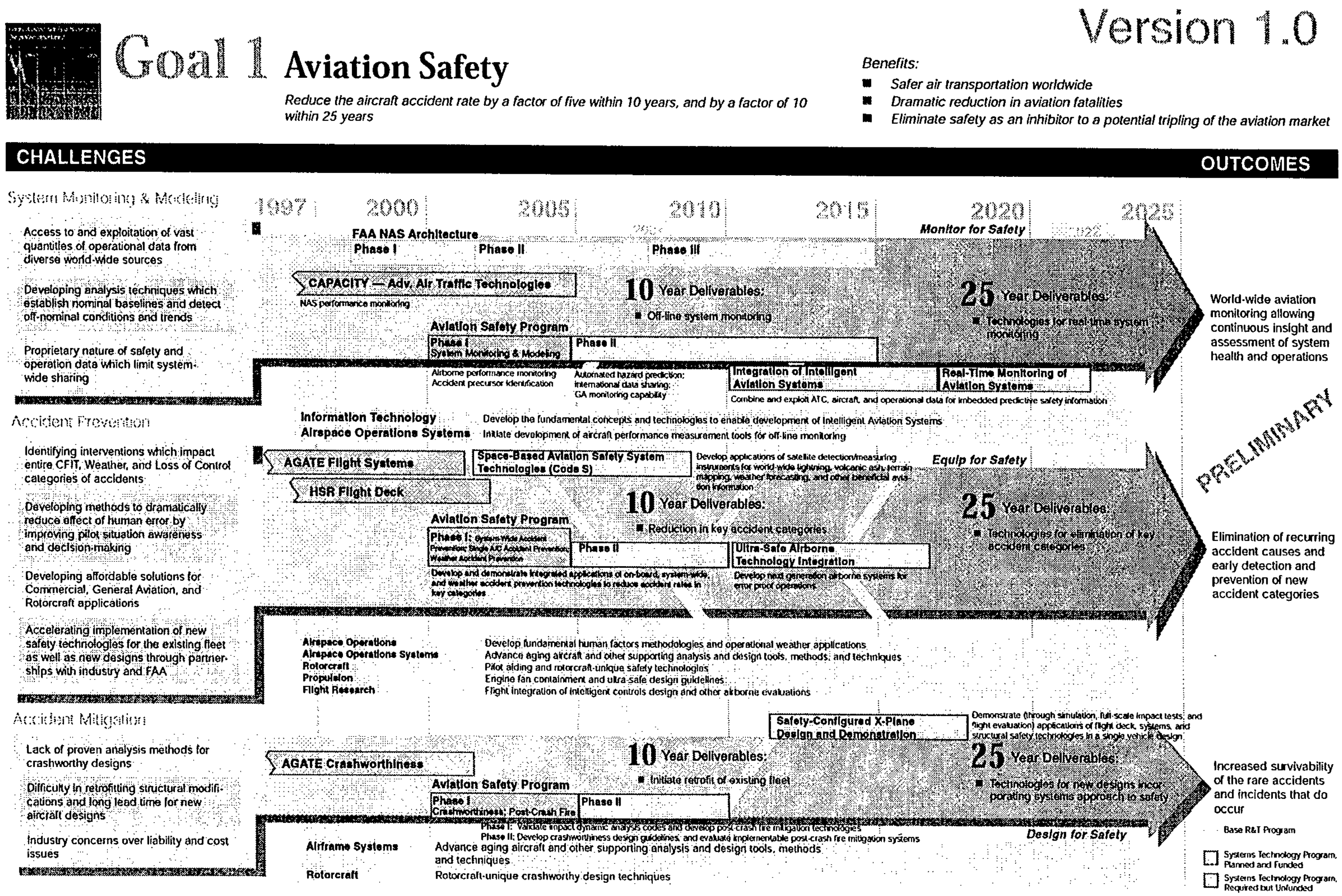

Figure 1. NASA Aviation Safety Program Roadmap

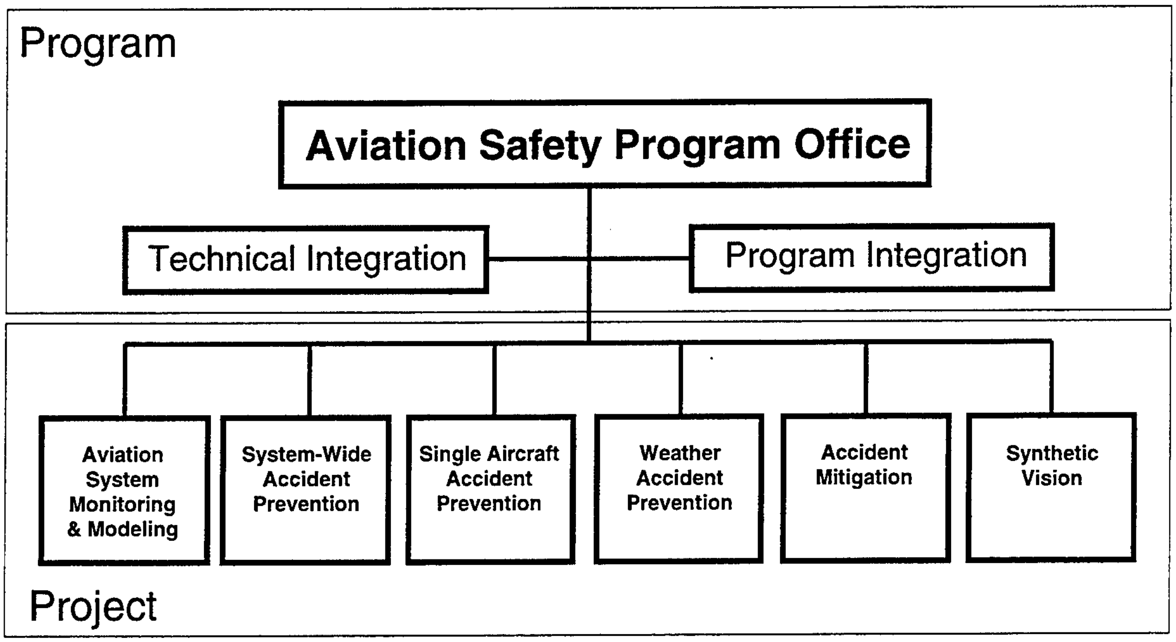

Figure 2. Aviation Safety Program Organization Chart

Aircraft Engine Health Management Data Mining Tools concentrates on the development of diagnostic and prognostic methods specifically for the propulsion system in order to improve safety. This will be achieved through the exploitation of technologies such as data mining and the consequent development of appropriate new data mining tools. These tools will be used for examining aircraft engine data in an effort to uncover unsuspected features in the data collected pertaining to the health and safety of the engine. Causal relationships between engine parameter trends and faults will be identified, as well as indicators of component damage accumulation and precursors to potential damage. The Glenn-led work will utilize off-line databases, and tools developed under this portion of ASMM will be primarily for use off-line, but may lead to better on-line tools as well.

2. APPROACH

The Aircraft Engine Health Management Data Mining Tools effort addresses both safety-specific and economic components of engine health management. Advances in areas such as fault precursor identification will improve the safety of air travel, and the enhanced safety can be delivered at a lower operational cost.

The fault precursor identification area will be addressed through the use of both maintenance and operational databases, which can reveal unknown correlations between engine parameters and component degradation and failures. During normal maintenance procedures, information regarding the type and amount of wear is recorded whenever parts are scrapped. Data mining methods provide the means to gain insight into damage accumulation mechanisms through the synthesis of information from simultaneous consideration of maintenance records and trended engine operational parameters. As the relationship between engine operating history and component wear becomes better understood, these parameters can be used to identify impending problems requiring maintenance action. This will certainly lead to safer

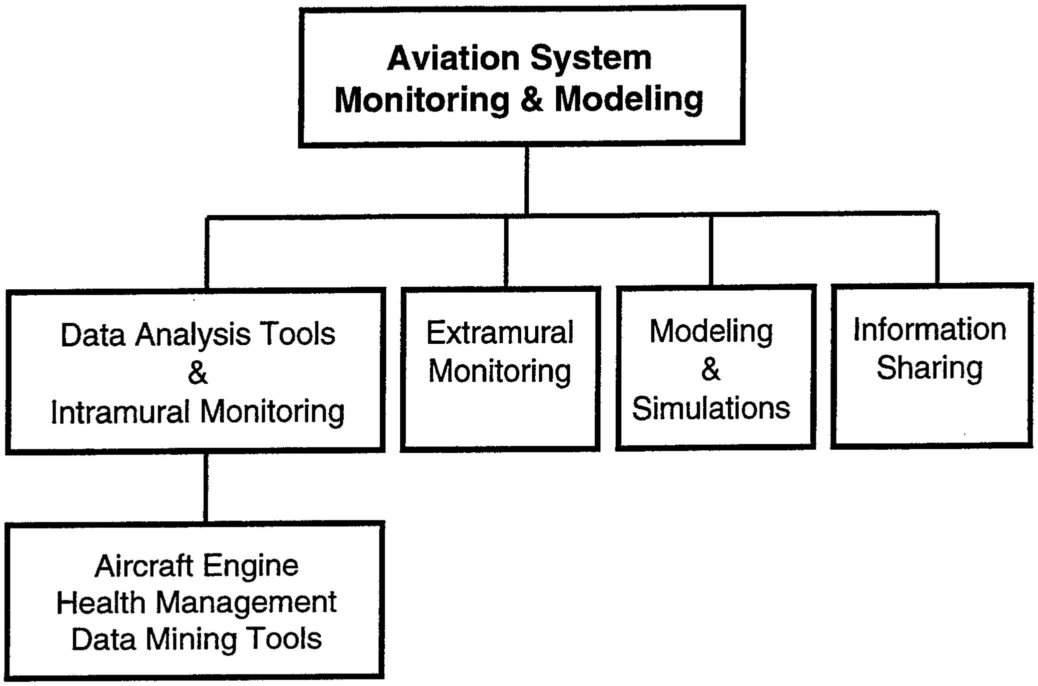

Figure 3. Aviation System Monitoring & Modeling Organization Chart

operation of the aircraft, but it has the side benefit of enabling *intelligent prognostics and logistics*. This concept not only allows maintenance to be performed on an as-needed or on-condition basis, but goes beyond that by recommending maintenance that is not quite due, but is advantageous to perform together with currently required maintenance. This scheme has the potential to greatly improve the efficiency of the maintenance procedure over current practice i.e. it will reduce downtime, manpower and materials costs and waste. Finally, the mining of maintenance data will lead to wear vs. operating history comparisons that can be used to demonstrate to operators how operating history impacts accumulated damage and thereby suggest changes that lead to component life benefit.

Although the work described here specifically deals with off-line processing and analysis, as does the entire ASMM thrust, this work has the potential to enable new types of on-line monitoring of engine health and life as relationships between engine variables are revealed. Generally it is understood that harsh environments are harder on engines than benign environments, but how might regular service between a particular city pair contribute to engine wear? What is the effect of flight path, cargo weight, or reduced thrust at take-off on the engine? What features can be attributed to airport procedures or frequency and duration of flights? These are the types of questions that can be addressed by mining the databases.

This approach is predicated on the existence and availability of appropriate databases. The ideal databases would contain many engine parameters recorded at a high frequency during all phases of flight. They would contain records of flights over several years from many engines, as well as the corresponding maintenance records. While data are available in different forms, locating and accessing databases that together make up an ideal data set is generally not a realistic possibility. Additionally, airline databases are highly proprietary. NASA and Pratt & Whitney are working with our airline partners to obtain data that will permit the development and demonstration of appropriate algorithms. This is still a challenge, however, as databases that are currently available tend to lack some desirable attributes. For instance, operational databases might contain many parameters, but at only a few operating conditions during the flight. This makes flight-to-flight trending possible, but real-time information is lost. Some in-flight databases recorded at higher frequency exist but they are missing other necessary features. For example, data from the Flight Operations Quality Assurance (FOQA) system—a system for the routine downloading and systematic analysis of aircraft parameters recorded during flight[2]—contains many parameters recorded at high frequency, but because it is so storage intensive, long term data availability becomes a limitation. Also associated workscope reports that are required for the work proposed here are not necessarily available. Maintenance records present their own problems. One of the main sources of confusion within these databases is called *shop data masking*. This is the result of the order in which defects are checked for and how they are subsequently recorded in the database. A common example involves the inspection for turbine blade damage. A blade may exhibit damage due to both oxidation and cracking, either of which is cause for scrapping. If the inspection reveals one of these defects the part is rejected and no further evaluation is performed. Thus only the information about the first type of damage is recorded; all other damage information is ignored. For data mining purposes it is important to distinguish between those cases where both types of damage were present and those cases where only a single type of damage occurred. Thus, current damage evaluation and recording procedures may lead to confusing results. Statistical techniques might be somewhat helpful in correcting this problem.

Damage and wear can certainly be linked to operational parameters through maintenance reports, but what about direct determination of degradation through analysis of the operational databases? Model-based fault detection and sensor validation work[3-5], whether based on known physical relationships or empirically derived relations, suggests that this is a very reasonable objective since variations in certain engine parameters are known to be correlated. Application of data mining tools to operational databases might be able to uncover more obscure relationships that until now have not been understood. Additionally, these relationships will likely be of a more discrete nature as opposed to continuous. That is, relating wear or fault occurrence to particular events or attributes such as operating environment (ambient temperature, atmospheric conditions) might prove to be where the breakthroughs are. The analytical relationships within propulsion systems are known to some extent through mathematical modeling, but the effect of discrete events on the engine are harder to quantify because they are often unaccounted for and they may be subtle. While the use of workscopes is essential for revealing the wear and damage accumulation behavior initially, the operational databases alone will be the key to obtaining up-to-date estimates of remaining component life. Taking this a step further, if the combined data sets can be used to identify fault precursors, timely evaluation of the operational data will allow faults to be predicted and preventive action to be taken to avoid them.

The notion alluded to above—that the utilization of variations in correlated parameters could supply additional information—leads to the subject of intelligent preprocessing of the databases. The raw data contain the same information as the processed data, but bringing out relationships that are already known makes the job of the data mining tools more straightforward. Advantages can be gained by using knowledge about the data set to correct, streamline, and/or augment it. Utilizing all available information should make the data more useful, while excluding information might lead to the discovery of awkward, overly complex relationships or even incorrect conclusions. For example, some on-wing repair procedures such as sensor replacement or water washes can result in performance changes[6]; if the cause is not accounted for, the data mining algorithms might attribute the changes to another source. Examples of how the data might be preprocessed intelligently include noise filtering, correcting to standard day conditions, exploiting some of the model-based relationships as mentioned previously, or Kalman filtering to incorporate estimates of additional parameters.

Use of data mining algorithms will help clarify which engine parameters are most important in the management of engine health. Conversely, they may highlight the fact that there are not enough sensed parameters to differentiate between two types of fault or to recognize a degradation mode, indicating the need for more sensors. This will help direct research in promising directions as the algorithms mature. Once the concept is proven viable and demonstrated to produce useful results, the data mining algorithms would dictate which variables should be recorded in flight and, given complete enough databases, at what frequency. The algorithms would also help refine recording procedures to be used during maintenance operations. This would effectively define a standard to which airlines would need to adhere in order to derive full benefit from these new techniques.

3. ROADMAP

The general outline given in the preceeding section is the basis for a proposed roadmap. This roadmap will be achieved through a combination of contract, grant and in-house work. Some of the work is already underway. The timeline for the effort extends from May 1999 (predating the official kick-off of the NASA AvSP) through 2002. This encompasses the planned funding profile for the NASA Glenn-led effort, Aircraft Engine Health Management Data Mining Tools.

Figure 4 lays out the roadmap on a timeline. The milestones indicated represent both initiated and planned work and expected outcomes. The milestones and associated deliverables and outcomes near the end of the program will be used to justify to the airlines the benefit of not only maintaining and monitoring engine data, but of standardizing their data-taking procedures.

The upper portion of the figure defines at a high level the elements of the Pratt & Whitney contract. The work performed in this portion of the program has the potential to convincingly demonstrate the power of these algorithms to the airlines since the data used are real, and Pratt & Whitney is an established engine supplier and maintenance provider. Briefly, the effort concentrates on using available maintenance and operational data to develop algorithms that characterize the damage to engine components as a function of equivalent engine cycles. These algorithms will then be restructured and generalized into a hierarchical set of tools capable of working with multiple component classes and damage modes. Tool sets at the various levels of the hierarchy will range from fundamental statistical routines to equivalent cycle and workscope estimation routines. Further refinement will continue through the end of the contract.

The lower portion of figure 4 depicts the rest of the NASA Glenn AvSP data mining efforts. At this point these include a university grant and potential in-house work. Other grants or contracts may be initiated before the end of the funding period for this Glenn-led work (September 2002). It is currently planned that any of the research performed under this area will utilize de-identified operational and maintenance data. This will help to legitimize the results in the eyes of the airlines, but the fact that the databases have been de-identified necessarily removes some possibly critical information, such as city pairs. Actual airline data (not de-identified) will be used if available.

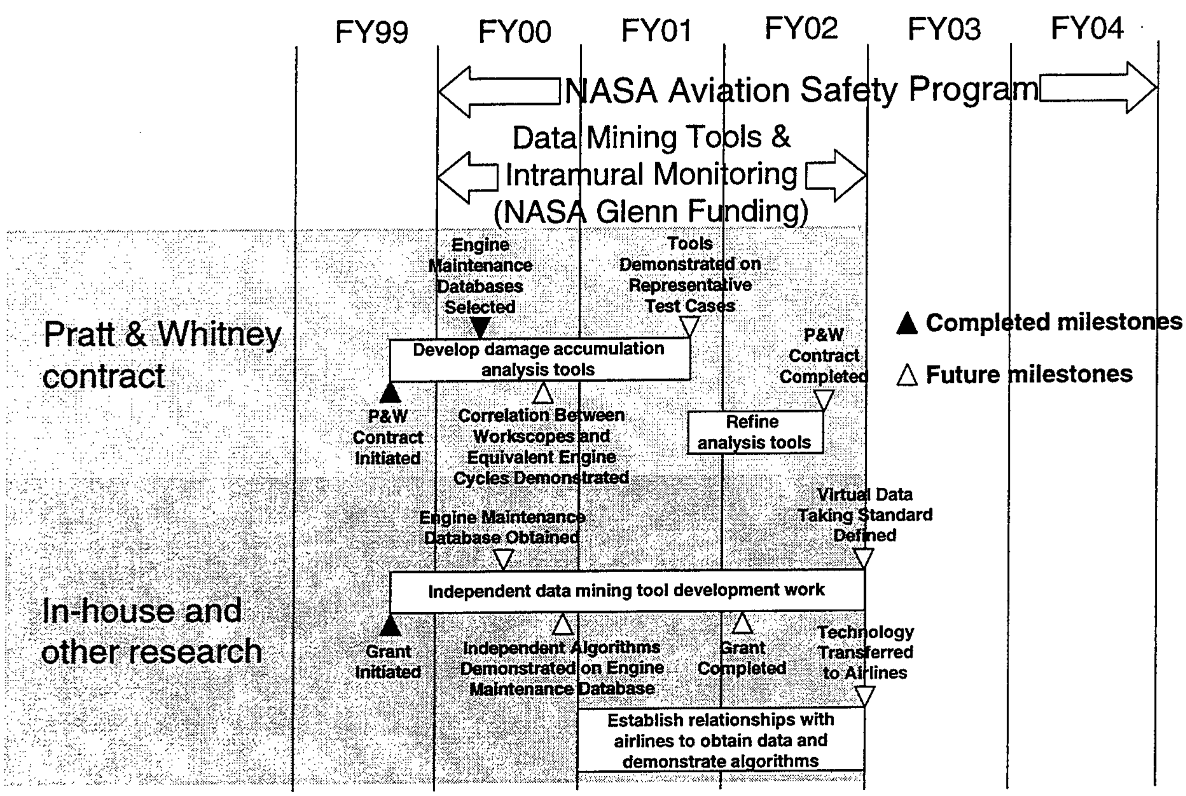

Figure 4. Roadmap for NASA Aviation Safety Program Aircraft Engine Health Management Data Mining Tools

Fundamental to the ultimate success of the program is technology transfer to the airlines. Working with our airline partners, NASA will seek to obtain additional data on which to demonstrate the data mining tools developed under this effort. Concurrently, NASA will demonstrate the capabilities of the tools to the airlines on the available databases. By the end of this program, the value of these tools will have been established.

4. SUMMARY

Aircraft Engine Health Management Data Mining Tools is an effort underway as part of the NASA Aviation Safety Program aimed at developing analytical tools to examine aircraft engine parameters measured in flight along with workscopes/maintenance reports. The eventual combination of these data through data mining tools will lead to the safer, more cost-effective operation of airlines due to the ability to make better technical and business decisions. The expected outcome of this work will be better engine health management, including fault precursor identification, life estimation of critical components, and improvement of engine life through modification of usage. The estimate of remaining component life will permit intelligent prognostics and logistics, incorporating optimal maintenance scheduling and on-condition replacement. While the obvious benefit of this is to reduce the cost of labor and need for replacement parts, this scheme should also identify premature wear or damage that is occurring to a part and alert operators to the need for replacement prior to a failure, thus enhancing safety.

It is the identification of safety-significant event precursors that will give the greatest safety payoff, since the avoidance of fatal accidents is the goal of the NASA AvSP. However, the fact that the roadmap addresses issues that provide more direct economic benefit should make the overall package very attractive to the airlines. As an outcome of this research, a virtual standard will define which engine parameters to monitor as well as how to record maintenance information. With this information and quantification of the potential benefits, hopefully our airline partners will see the value of conforming to the standard and thus reap the rewards.

Overall, the main benefits of this program are envisioned to be: increased safety; minimization of combined cost of maintenance and operation though usage modification; enhanced reliability through the anticipation of faults before they occur; accurate prediction of remaining life in parts and components; discovery of new relationships in data to enhance safety and reliability.

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