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Program Plan

Aircraft Catastrophic Failure Prevention Research Program

January 1994

U.S. Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City International Airport, New Jersey 08405

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16. Abstract

At least eight tragic civil transport aircraft accidents worldwide since 1979 that resulted in over 1100 fatalities, prompted Congress to enact the legislation which directed the Federal Aviation Administration (FAA) to establish the Aircraft Catastrophic Failure Prevention Research Program. The legislators were motivated by the fact that in each accident the devastating consequence may have been prevented. Specifically, the Program contained in the Omnibus Reconciliation Act of 1990 (Public Law 101-508) stated that improved methodology and advanced technology be applied to assess and prevent catastrophic failures that can result in civil aircraft accidents. The Program further expanded the FAA's research role which had just recently been broadened under the Aviation Safety Research Act of 1988 (Public Law 100-591).

The goal of this program is to prevent catastrophic failures and if prevention is not feasible, to mitigate the effects of such failures to allow for continued controlled flight to a safe landing. This research program is inclusive and addresses all components of a civil aircraft, e.g., turbine engines, airframes, flight control systems, and man-machine interfaces. Safety of flight depends on each component functioning properly and all functioning together as they were designed to do. Thus, a systems approach is followed in the analysis of each component to address cascading of failures by related components. A failure risk assessment is performed for each aircraft system to define threats and vulnerabilities. This analysis is the basic tool used to identify and evaluate deterrent technologies. When technology is not effective in deterring a threat, mitigation measures are applied to avoid a catastrophic event.

The program plan is presented in four sections. Section One provides background information and a technical overview of the program. Section Two deals with the prevention of catastrophic turbine engine failures and/or the isolation of flight critical systems and occupants from such failures. Section Three concentrates on airframe design, manufacturing, and maintenance technologies which can prevent or mitigate the effect of structural failures. Section four address the prevention of loss of critical flight control system functions after a failure and determines possible design concepts that will provide alternate means of control. The human interface is also addressed within the context of flight control system research.

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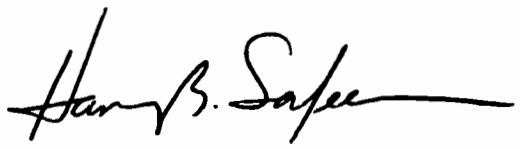
FOREWORD

The fundamental mission of the Federal Aviation Administration (FAA) is to foster a safe and efficient air transportation system. With respect to safety, our goal is to establish an operating environment that ensures an error free system and produces no accidents or fatalities. As part of the process to meet this goal our aircraft safety research and development activities continually search for technology to ensure the safety of aircraft components and systems with respect to certification, operation, and continued airworthiness.

The scope of FAA aircraft safety research was impacted significantly when Congress passed the Aviation Safety Research Act of 1988. Two years later, this legislation was followed by another Congressional initiative in Public Law 101-508 which established the Catastrophic Failure Prevention Research Program. These legislative changes broadened the FAA safety research mandate and provided new authority for accessing the best minds in American research to assist in improving aircraft safety technology.

To accomplish these new research mandates, the FAA has prepared a series of comprehensive research program plans. I am pleased to introduce this first edition of the FAA Aircraft Catastrophic Failure Prevention Research Plan. The development of this plan involved input from technical experts throughout the FAA. I expect it to evolve as advanced technologies and new research participants are brought to focus on aircraft catastrophic failure prevention. I am confident that the research outlined in this plan will lead to a demonstrable increase in aviation safety.



Harvey Safeer, Director
FAA Technical Center

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LIST OF ABBREVIATIONS

AC	Advisory Circular
ACES	Aircraft Command in Emergency Situations
AIR	Aerospace Information Report
APU	Auxiliary Power Unit
CIS	Commonwealth of Independent States
DFBL	Digital Fly-By-Light
DFBW	Digital Fly-By-Wire
DoD	Department of Defense
FAA	Federal Aviation Administration
FAR	Federal Airworthiness Regulation
FBW	Fly-By-Wire
FCS	Flight Control System
IBU	Independent Back-Up
JAA	Joint Airworthiness Authority
JAR	Joint Airworthiness Regulation
MEL	Minimum Equipment Lists
MMEL	Master Minimum Equipment Lists
NASA	National Aeronautical Space Administration
NAWCAD	Naval Air Warfare Center, Aircraft Division
NDI	Non-Destructive Inspection
NRS	National Resource Specialists
PR	Pilot Rating
SAE	Society of Automotive Engineers
SCAS	Stability and Control Augmentation Systems
SRTF	Systems Review Task Force

EXECUTIVE SUMMARY

At least eight tragic civil transport aircraft accidents worldwide since 1979 that resulted in over 1100 fatalities, prompted Congress to enact the legislation which directed the Federal Aviation Administration (FAA) to establish the Aircraft Catastrophic Failure Prevention Research Program. The legislators were motivated by the fact that in each accident the devastating consequence may have been prevented. Specifically, the Program contained in the Omnibus Reconciliation Act of 1990 (Public Law 101-508) stated that improved methodology and advanced technology be applied to assess and prevent catastrophic failures that can result in civil aircraft accidents. The Program further expanded the FAA's research role which had just recently been broadened under the Aviation Safety Research Act of 1988 (Public Law 100-591). The 1988 Act emphasized the importance of long-range research and development to provide the flying public with the safest and most efficient air transportation system possible.

The goal of this program is to prevent catastrophic failures and if prevention is not feasible, to mitigate the effects of such failures to allow for continued controlled flight to a safe landing. This research program is inclusive and addresses all components of a civil aircraft, e.g., turbine engines, airframes, flight control systems, and man-machine interfaces. Safety of flight depends on each component functioning properly and all functioning together as they were designed to do. Thus, a systems approach is followed in the analysis of each component to address cascading of failures by related components. A failure risk assessment is performed for each aircraft system to define threats and vulnerabilities. This analysis is the basic tool used to identify and evaluate deterrent technologies. When technology is not effective in deterring a threat, mitigation measures are applied to avoid a catastrophic event.

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The Aircraft Catastrophic Failure Prevention Program is a cooperative effort between Federal agencies, private industry, and academia. Many of the technologies addressed in the program plan are now in a state of rapid advancement. Thus, while the program plan is as detailed as is now possible, it is flexible enough to change direction to take advantage of emerging technology.

1.0 INTRODUCTION

Civil aviation accidents like the crash of United Flight 232 on July 19, 1989, are devastating and deadly. While cruising at an altitude of about 35,000 feet, the DC10's tail-mounted center turbine engine experienced a fan disk failure. High energy disk fragments liberated from the engine cut through hydraulic lines, resulting in immediate and near total loss of all flight controls. The aircraft crashed at the Sioux City, Iowa Airport as it was attempting an emergency landing. There were 112 fatalities out of the 296 passengers and crew onboard. The accident investigation concluded that this was a preventable accident (*Reference 1*). *Figure 1.1* shows a post-crash, top view of Flight 232's tail engine nacelle and horizontal stabilizer damage. Other preventable civil aircraft accidents have also resulted in tragic consequences. The 1985 rupture of the aft pressure bulkhead on a Boeing (B)747 severely damaged the empennage, causing the aircraft to crash with the loss of all 520 persons on board. On February 24, 1989, a cargo door blew off a B747 while flying over the Pacific Ocean. Nine occupants were sucked out of the aircraft and fell to their deaths. On April 28, 1988, a 19-year old B737 lost a major part of its upper fuselage in flight due to undetected multiple fatigue cracks; a flight attendant died and many passengers were injured.

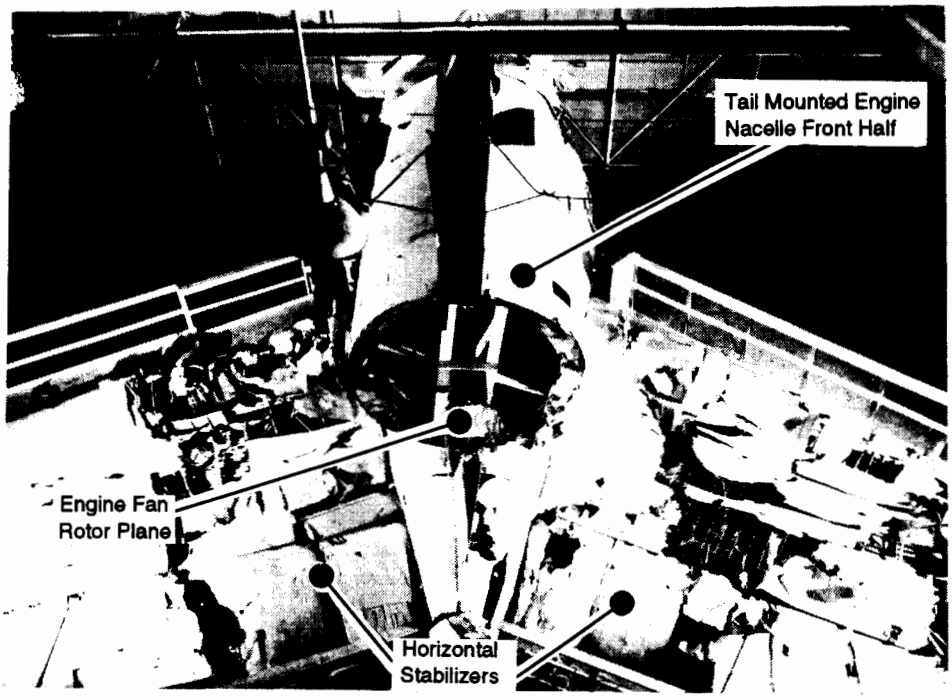

Figure 1.1: Post-Crash View of Flight 232 Aircraft Empennage Damage

1.1 FAA RESEARCH MISSION

The Federal Aviation Administration (FAA) has the responsibility to foster a safe and efficient civil air transportation system. That responsibility was established by the Federal Aviation Act of 1958. Simply stated, the safety goal of the FAA is to eliminate problems which cause accidents and fatalities like those just described.

The 1958 Act provides the FAA Administrator with the authority to "undertake or supervise such developmental work and service testing as tends to the creation of improved aircraft, aircraft engines, propellers, and appliances." (Section 312). This guidance provided a direction for the FAA's research toward the applied end of the technical spectrum. Section 312 provides no mandate for technological improvements by the FAA when the needed devices and materials are not available for development and service testing.

The FAA research mission was drastically altered by the Aviation Research Act of 1988 which amended Section 312 by adding the following: "The Administrator shall undertake or supervise research to develop technologies and to conduct data analyses for predicting the effects of aircraft design, maintenance, testing, wear, and fatigue on the life of aircraft and on air safety, to develop methods of analyzing and improving aircraft maintenance technology and practices (including nondestructive evaluation of aircraft structures), to assess the fire and smoke resistance of aircraft materials, to develop improved fire and smoke resistant material for aircraft interiors, to develop and improve fire and smoke containment systems for in-flight aircraft fires, and to develop advanced aircraft fuels with low flammability and technologies for containment of aircraft fuels for the purpose of minimizing postcrash fire hazards." The 1988 act authorized the FAA to generate technology breakthroughs where technology gaps need to be closed.

The FAA's research mission was again changed with passage of the Aircraft Catastrophic Failure Prevention Program under the Omnibus Reconciliation Act of 1990 (P.L. 101-508). The 1990 Act further amended Section 312 with the following requirement: "to develop technologies and methods to assess the risk of and prevent defects, failures, and malfunctions of products, parts, processes, and articles manufactured for use in aircraft, aircraft engines, propellers, and appliances which could result in a catastrophic failure of an aircraft." While Section 312 was originally focused on improvements to airplanes, the 1990 amendments add emphasis on research to make airplanes free from catastrophic failure.

The FAA has prepared program plans for the research needed to meet specific goals prescribed in the 1988 and 1990 Acts. There are two program plans related by a

common goal, i.e., increasing aviation safety, and by the fact that some technologies will be applicable to both programs. Thus, a short description of the Aircraft Safety Research Program, which is responsive to the 1988 Act, is provided here as part of the introduction to this Aircraft Catastrophic Failure Prevention Research Program.

1.2 THE FAA AIRCRAFT SAFETY RESEARCH PROGRAM

For the past 20 years, the aircraft accident fatality rate has remained nearly level at just under 2 deaths per 10 million passengers carried. With the increasing number of passengers carried each year, maintaining a level fatality rate means an increase in the total number of fatalities each year. If the current stable rate continues over the next decade, total aviation fatalities would be expected to rise by about 30 percent simply due to growth in the number of passengers carried. Thus, the FAA's goal is to reduce this fatality rate. The data also indicates that new safety problems arise as old ones are eliminated, and some simply continue to persist. New problems may reflect the application of new technologies to transport aircraft, e.g., the march toward digital fly-by-wire control systems. However, as aircraft designers adopt fly-by-wire systems, many of the problems associated with mechanical flight control systems will disappear.

The objective of the Aircraft Safety Research Program (*Reference 2*) is to develop the new technologies needed to improve safety and bring down the fatality rate. Major areas of concern include reliable and effective airframe designs, propulsion systems, flight controls, and electrical systems. The program includes the research needed for aircraft to be able to withstand in-flight hazards such as lightning, bird strikes, turbulence, icing, and electromagnetic interference. Other priorities include occupant crash impact survivability, preventing post-crash fire, emergency evacuation, flight load induced structural fatigue, and corrosion. Therefore, the Aircraft Safety Research Program establishes the FAA safety umbrella under which all safety research activity resides.

The FAA carries out its safety role by promulgating regulations, developing procedures to implement the regulations, and certifying airman, aircraft, airlines, airports, maintenance, and production facilities. The Aircraft Safety Research Program provides the knowledge base which enables the FAA to regulate, certify, and advise these components of the air transportation system.

Establishing, executing, and enforcing aircraft safety standards are crucial to assuring aircraft safety. The FAA's regulatory responsibilities are contained in Section 601 of the 1958 Act and charge the FAA Administrator with the "duty to promote safety of flight of civil aircraft in air commerce by prescribing and revising from time to time:

(1) Such minimum standards governing the design, materials, workmanship, construction and performance of aircraft, aircraft engines and propellers as may be required in the interest of safety;

(2) Such minimum standards governing appliances as may be required in the interest of safety."

To carry out these responsibilities, FAA regulatory personnel frequently require technical data and other information that are not readily available. In these cases, specific research and development are necessary to support their needs.

1.3 THE FAA AIRCRAFT CATASTROPHIC FAILURE PREVENTION RESEARCH PROGRAM

The Aircraft Catastrophic Failure Prevention Research Program adopts the 1990 Act's definition that catastrophic failure: "is any defect, failure and malfunction of products, parts, processes, and articles manufactured for use in aircraft, aircraft engines, propellers, and appliances which could result in a catastrophic failure of an aircraft." The program's foundation is based on developing methodologies to characterize, assess, and define the risk of catastrophic failures. Risk assessment is focused on single point failures identified by this and other research programs, e.g., engines, airframes, and flight controls. Risk assessments can then be linked to evaluate potential cascading of the effects of single point failures throughout the aircraft. The analysis will also address those parameters which degrade airworthiness and threaten occupant survivability, e.g., fire, depressurization, aerodynamic forces, airframe and critical system integrity. This program will adopt state of the art technology currently being developed by the Department of Defense (DoD), National Aeronautical Space Administration (NASA), and other FAA programs such as the Aviation Security Program.

As failure mechanisms and risk to the aircraft are defined, technologies which can deter the threat to the aircraft will be selected for evaluation and application. While some candidate technologies are under development within the FAA, others will be imported from external sources, e.g., other government agencies, industry, and academia.

Figure 1.2 is a schematic overview of the Aircraft Catastrophic Failure Prevention Research Program. Major inputs to the program are data describing current and proposed aircraft designs and their development and operational characteristics. This program will support the transfer and application of technology from other programs in

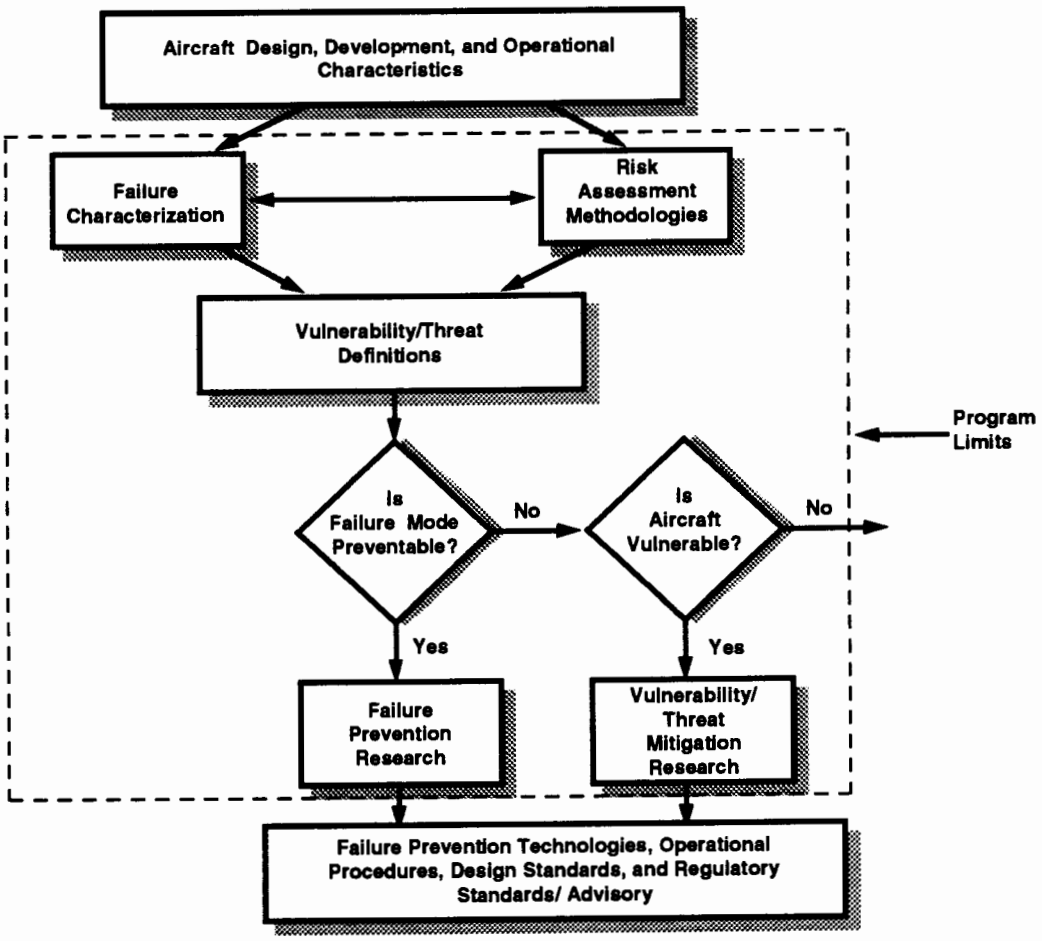

Figure 1.2: Aircraft Catastrophic Failure Prevention Research Program

the areas of analysis methodologies, failure mode prevention, and threat mitigation. Support may be obtained through joint programs with many Federal research agencies, including defense conversion into dual use technology initiatives, or by directed research performed for FAA by academia, national laboratories, and private industry.

Primary program outputs will include descriptions of applicable aircraft failure prevention technologies, data supporting certification and operational requirements, design standards, and regulatory materials.

Significant input to the development of this research program was provided by the FAA Research and Development Advisory Committee's Transport Airplane Safety Subcommittee (*Figure 1.3*). The subcommittee's charter is to consider the adequacy of research programs, both current and proposed, for aircraft survivability and airworthiness. System review task force groups were established to consider continued airworthiness assurance, specific airframe design philosophy for flight critical systems, turbine engine hazards, and other hazards as defined. (*References 3 through 8*)

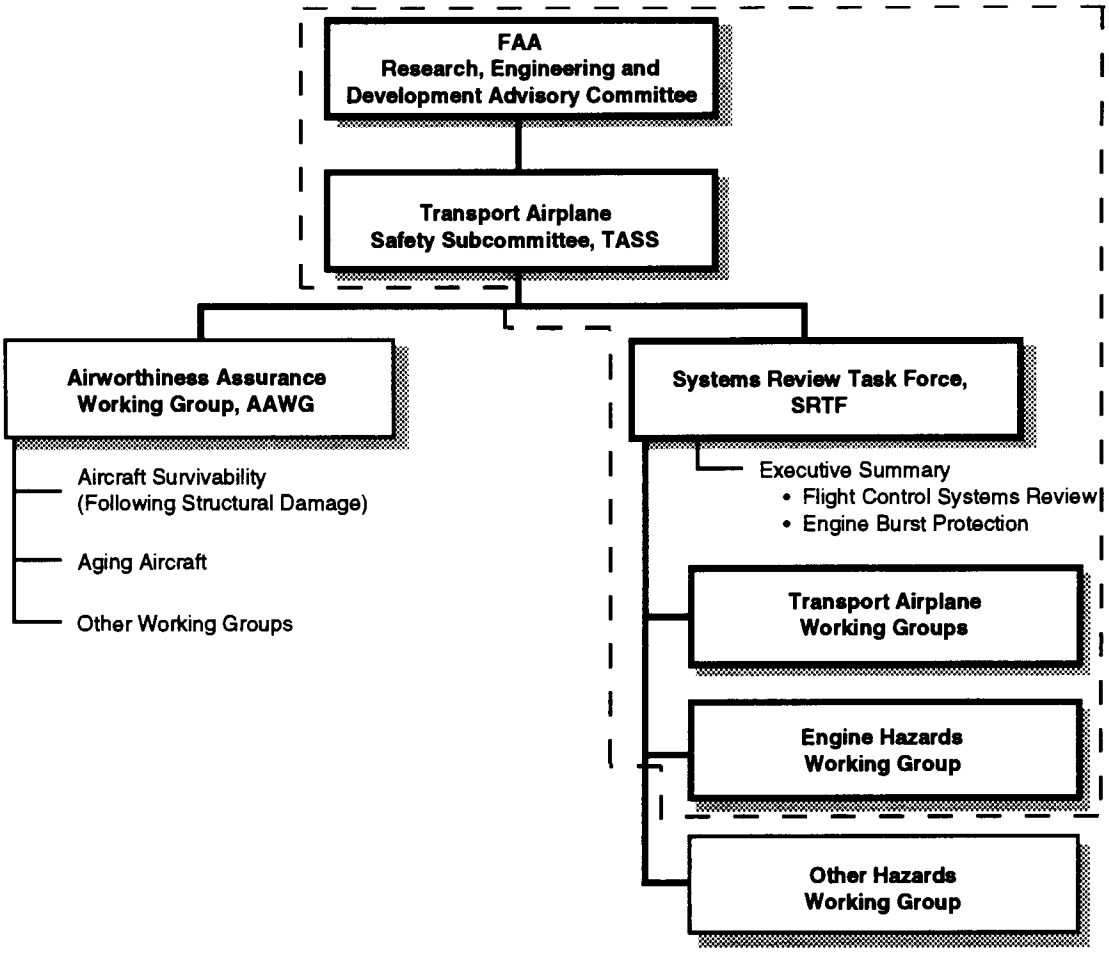

Figure 1.3: FAA Research, Engineering and Development Advisory Committee

This program will continue to depend on guidance and support from many elements of the FAA, including the following:

- Transport Airplane Directorate
- Small Airplane Directorate
- Engine Directorate
- Rotorcraft Directorate
- National Resource Specialist(s)
- Aircraft Evaluation Group(s)
- Associate Administrator for Aviation Safety
- Flight Standards Service
- Aircraft Certification Service
- Engineering, Research and Development Service
- Office of Accident Investigation

In accordance with the requirements of the Aircraft Catastrophic Failure Prevention Program legislation, a process will be established to regularly disseminate information from this program to the public. The results of, and progress by, all tasks necessary for overall program integration and completion will be reported. Information will be disseminated in various formats, e.g., workshops, symposia papers, formal reviews, prototype demonstrations, and technical reports.

Universities and nonprofit research laboratories will be identified as potential Centers of Excellence in the technical specialties critical to catastrophic failure prevention research. The FAA will solicit proposals from qualified organizations to demonstrate their competency in particular technical areas. The FAA will review and evaluate proposals in accordance with established procedures and make competitive selections based on merit and relevancy to the technical specialty.

The following sections of this program plan address three broad categories of aircraft systems, i.e., turbine engines, airframes, and flight control systems. In the interests of simplified organization, all aircraft hardware and software are considered to fall into these categories. Environmental issues, fire hazards, and man-machine interfaces are considered in each category. The vulnerability and survivability of critical aircraft systems that are exposed to threats of single point failures are the major part of this analysis. However, the program's philosophy does not consider the three categories to be independent when viewed from a catastrophic failure prevention perspective. Each category may be influenced by risk assessments in other ones, particularly with regard to the probability of cascading failure modes producing serious secondary damage.

2.0 TURBINE ENGINE FAILURE PREVENTION

2.1 INTRODUCTION

Aircraft gas turbine engines and auxiliary power units (APU) employ rotor systems designed for continuous operation at the severe stress levels generated by high cyclic rotational speeds and temperatures, and exposure to high gas path pressure loadings. Rotor components will fail (*Figure 2.1*) when material properties deteriorate below minimum necessary strength levels or when they are exposed to nondesign operating conditions such as excessive over-speed, over-temperature, and foreign object ingestion. Faulty assembly or the failure of other engine components can result in excessive mechanical or thermal loads on the rotor hardware, leading to failure.

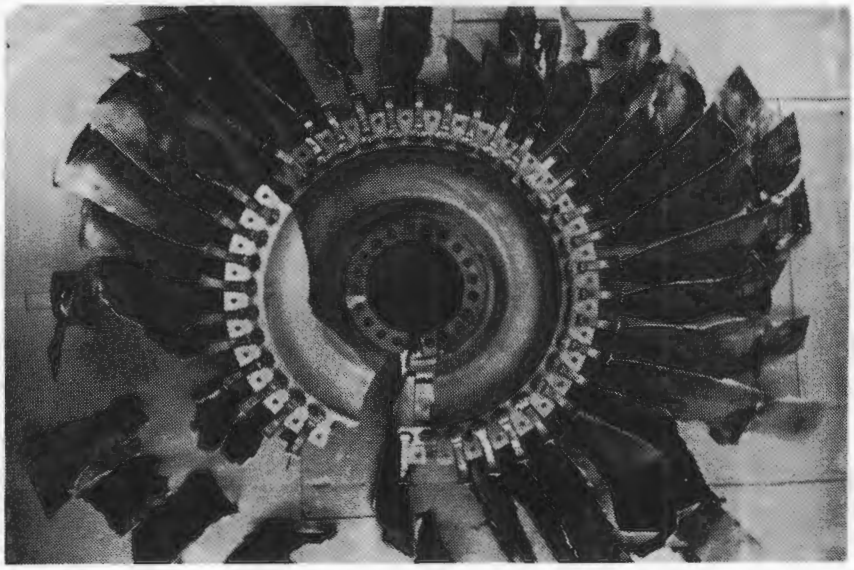

Figure 2.1: Liberated Fan Disk Fragments

A major rotor failure results in the release of high energy fragments which are dispersed at high velocities. *Figure 2.2* illustrates generic radial fragmentation patterns for a typical rotor stage in the fan, compressor and turbine sections of an engine (*Reference 9*). In an actual failure, liberated fragments will disperse circumferentially in all directions and in randomly positioned pie-shaped segments. Accident data has reported the radial dispersion angles of the fragments to be larger than shown, and blade fragments to exit the inlet duct and exhaust nozzle axially.

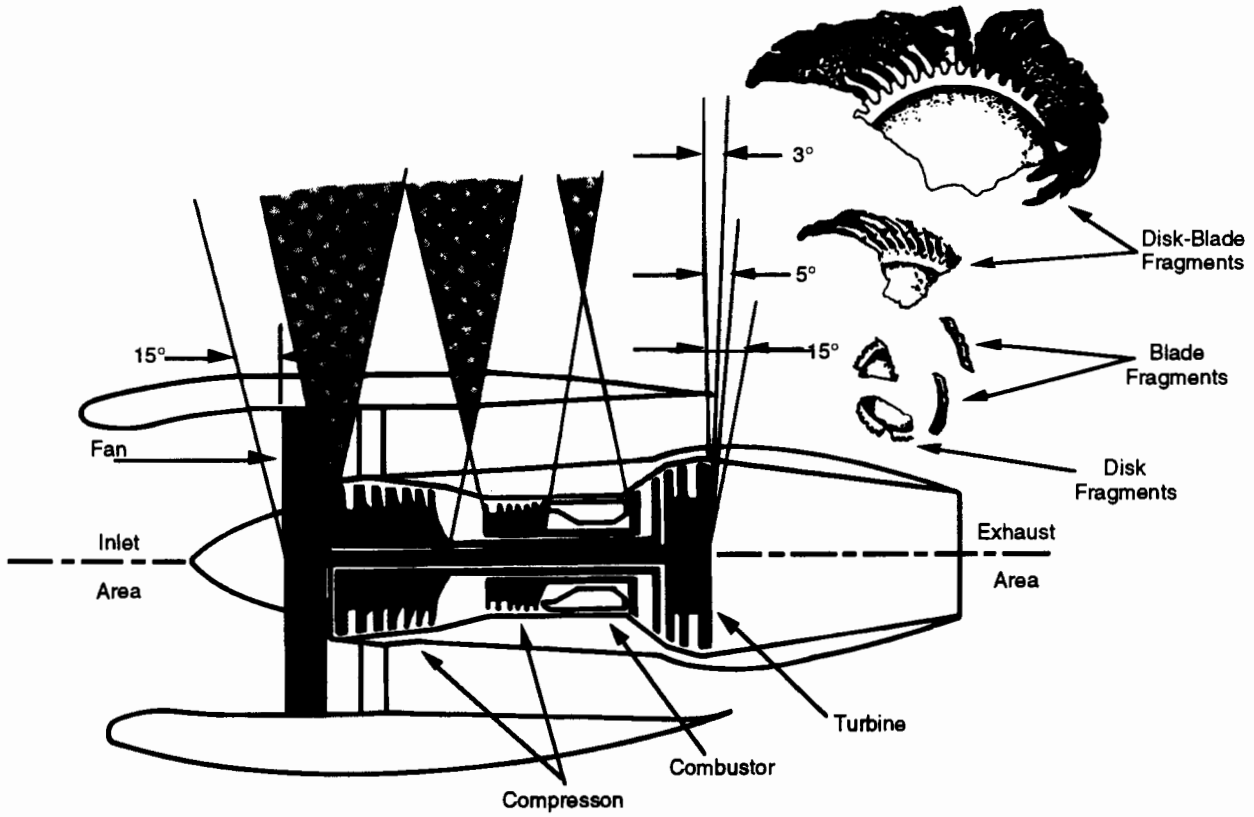

Figure 2.2: Estimated Path of Fragments From an Uncontained Rotor Failure

When fragments penetrate or escape the engine casing, the FAA refers to the event as an "uncontained failure". The consequence of an uncontained failure is usually the immediate and permanent loss of power and the possibility of damage to the airframe flight critical structures, systems, controls, and other engines. Such damage can lead to fire, loss of control, hull loss, and occupant injury or death.

Federal Airworthiness Regulation (FAR) Part 33 contains standards for turbine engine rotor system integrity. These standards address the structural integrity aspects of low-cycle fatigue, rotor overspeed, and vibrational stresses in rotor disks, shafts, and blades or vanes. FAR Part 33 also sets fan, compressor, and turbine case design standards for the containment of a single failed blade. FAA Advisory Circular 33-5 (*Reference 10*) provides the means of compliance to this standard. However, operational data for the US commercial aviation turbine powered fleet shows that between 1976 and 1986, there were 92 incidents, with known causes, of uncontained engine rotor failure. Of the 92 incidents; 35 were attributed to design and life prediction problems, 40 were attributed to secondary causes, i.e., failure events initiated by other engine components or conditions that resulted in an uncontained rotor failure. Of the remaining 17 incidents; 12 were

foreign object damage, four were due to quality control, and one was caused by faulty assembly or inspection.

The FARs also contain airframe certification standards that address engine rotor system safety. For normal utility and acrobatic category aircraft, covered under Part 23, and transport category aircraft, covered under Part 25, the standards require that design precautions be taken to minimize the hazard to the aircraft in the event of an uncontained rotor failure. The FAA has issued a Notice of Proposed Rule Making for transport category rotorcraft, covered under Part 29, to incorporate the same requirement. FAA Advisory Circular (AC) 20-128 (*Reference 9*) provides the means of compliance for these certification standards. Research may be required to support an Aircraft Regulatory Advisory Committee proposed update to AC 20-128.

Another potential for catastrophic failure is engine combustor case burn-through. Although combustor chamber design has continually improved, service experience shows that turbine engine case burn-throughs continue to occur. Preventative and protective measures for combustor burn-through have been established the same way as for rotor fragment liberation and they are addressed in FAA Advisory Circular 20-135 (*Reference 11*).

2.2 BACKGROUND

Published reports on in-service rotor system failures for the US commercial turbine engine powered fleet since 1976 show that uncontained blade failures continue to occur at a low but fairly regular rate (*Reference 12*). In its report on this subject, the Society of Automotive Engineers (SAE) noted the following:

> "Disk failures have been the foremost cause of non-containment fragments causing severe aircraft damage (such as crash landing, loss of aircraft, critical injuries, and fatalities). For events causing severe aircraft damage, 88 percent were due to disks of which 20 percent were commercial transport, zero percent general aviation and 80 percent rotorcraft. For those events causing significant aircraft damage (such as damage to primary structure or systems, uncontrolled fire, rapid depressurization, loss of power on an additional engine, and minor injuries) 70 percent were due to disks of which 40 percent were commercial transport, 10 percent general aviation, and 50 percent rotorcraft."

These data are illustrated below in *Figure 2.3.*

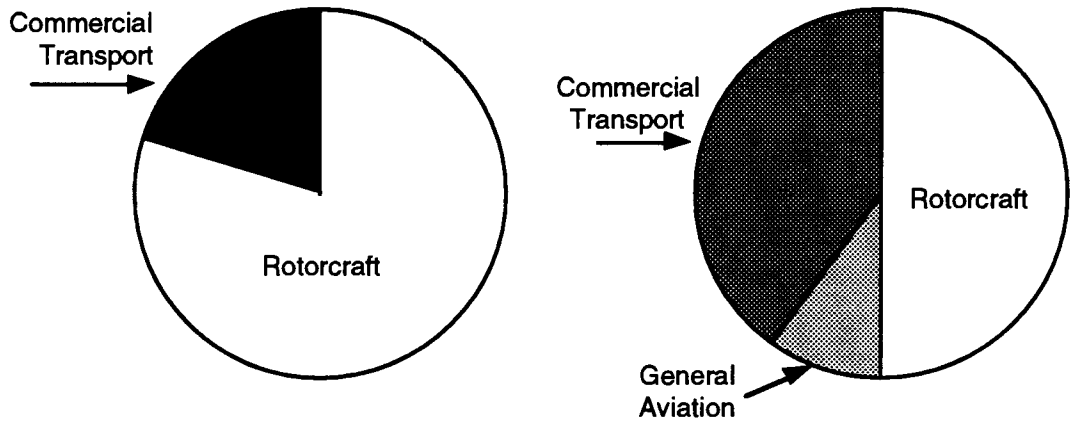

Figure 2.3: Damage Caused by Engine Rotor Disk Failure

The Engine Hazard Working Group (see Figure 1.3) was formed in October 1989 by members of industry and the FAA to address issues on aircraft survivability and to determine if current engine containment design practices are the best that can be implemented, or if improvements are practical for current and future designs. The group reviewed previous SAE reports, service bulletins, industry practices for repair and inspection, and disk and blade containment practices. The group determined that the aircraft industry did not appear to be on the verge of making any new breakthroughs in containment technology. They then recommended that the current state-of-the-art in engine containment and aircraft shielding for uncontained disks be reviewed and documented. Furthermore, they recognized that improved blade containment is needed and they provided a list of issues that should be considered in future engine designs and certification standards (*Reference 8*).

AC20–128 recommends four practical design precautions to minimize the hazard to an aircraft from an uncontained rotor failure from either a turbine engine or an APU.

1. Location of engine or an APU potential rotor and blade fragments relative to critical components, systems or areas of the aircraft.

2. Location of critical systems and components relative to likely fragment dispersal areas.

3. External shield and deflector devices or structure.

4. Appropriate aircraft modifications.

While the potential for an uncontained rotor failure to cause an aircraft loss is clearly recognized, the actual number of losses has been limited by selective use of the four primary hazard prevention methods. Quality design, manufacturing, and maintenance practices have resulted in high turbine engine reliability. Installation constraints such as remote, protected locations for engines and redundant critical systems minimize hazardous failures. Airframe designers attempt to isolate engines and APUs from flight critical systems to minimize the likelihood that an engine failure will result in damage to systems necessary for the safety of flight. While much has been done, the wider application of containment or protective shields, as well as improved rotor system diagnostics, inspection techniques, manufacturing standards, design concepts and service life prediction methods will provide for even greater hazard reduction.

Improving fleet-wide turbine engine failure hazard safety is a multidimensional problem. Turbine engines are designed to meet specific performance, weight, ingestion, and environmental considerations. Turbine engines also come in a wide variety of types, sizes, and applications. Older fixed-wing aircraft are often powered by turbofan engines with small fan diameters and relatively low fan bypass ratios in the 1.5 to 1 regime. Newer aircraft designs use large diameter engines with higher bypass ratios in the 5.0 to 1 regime. Future propulsion systems are expected to have even larger diameter engines and higher bypass ratios. Turboprop and turboshaft engines come in a wide variety of sizes and configurations. Turboprop engines power fixed-wing aircraft propellers. Turboshaft engines power helicopter rotors. Auxiliary power units are small turbine engines used on aircraft to provide electrical and pneumatic power. Each design and application must be considered to understand all of the potentially hazardous failures.

With the wide range of turbine engine designs and applications, certain research has greater significance in specific application areas. For instance, rotating parts containment may be more significant as a safety improvement for helicopters, where closely spaced twin engines are common, then for fixed wing aircraft with more separation between engines. While all turbine engines certified under FAR Part 33 must be able to contain one blade from each of the fan, compressor, and turbine stages, subsequent release of hazardous uncontained blade and disk fragments still occur. Failures have resulted in fragment penetration of fuel tanks, structures, fuselages, system components, and other aircraft engines.

2.3 TECHNICAL APPROACH

The technical approach to turbine engine failure hazard prevention research divides the problem into the major tasks shown in *Figure 2.4*. Task I focuses on failure

characterization, risk assessment, and failure threat definition. Task II focuses on failure mode prevention. Task III looks at aircraft protection from nonpreventable hazards.

The research initiatives for this program are based in part on the findings of the FAA Titanium Rotating Components Review Team (*Reference 13*). The team was organized in response to the investigation of the United DC10 accident at Sioux City. The review team considered design, manufacturing, quality control, and inspection procedures and techniques used in the production of titanium alloy high energy rotating life-limited components of turbine engines. The investigation documented the need to improve titanium engine rotor components from the initial material processing through final acceptance and in-service inspections.

The primary hazard of turbine engine rotor failures is high energy rotating component fragment liberation from the engine into the aircraft, i.e., uncontained failure. To understand component fragment liberation, the component's critical origin, i.e., disk bore, web, rim, etc. for failure, and the expected aircraft operating conditions must be understood. This will result in accurate analytical fragment liberation models which can be developed for a wide range of conditions. This program intends to utilize this and other information from accident reports and testing to properly determine hazard prevention and protection capabilities. Technology that extends the safe operating life of rotor components while reducing risk of failure is vital. Current FAA propulsion research programs will determine risk assessments, fault diagnostics and containment of failed components as explained in sections 2.3.1-2.3.3. As these technologies are developed, the program will evolve and lead the way to further minimize the possibility of a catastrophic turbine engine failure.

Failure characterization is the first step in determining the hazard potential of a specific failure. The initial failure mode may be characterized by fragment liberation or combustor burn-through. The program will review the records of component tests, manufacturer analyses, and engine failure data developed for accident and incident investigations. Failure characteristics that affect the component or rotor system life will be identified from the component tests. The manufacturer analyses will provide design limitations and operating environment effects that were used to determine the component or rotor system life. This information will allow failure characterization to be defined for specific components or complete rotor systems. The incident and accident reports will be utilized to determine which components are more critical and how they affect other systems when they fail. Failure characterizations then supports risk analysis studies that can determine the probability of occurrence and catastrophic consequence.

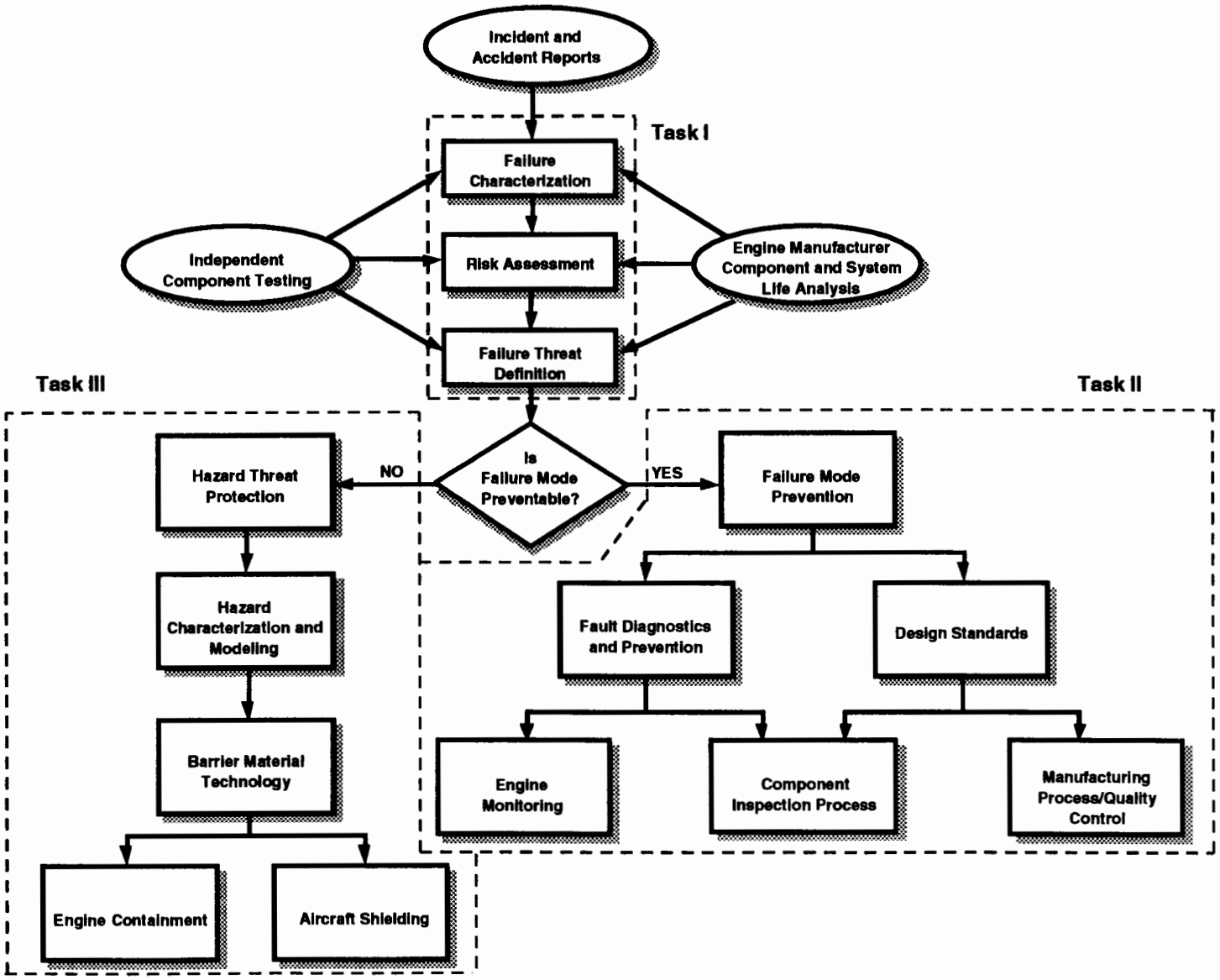

Figure 2.4: Turbine Engine Failure Prevention — Flow Chart

2.3.1 Task I: Failure Characterization, Risk Assessment, and Failure Threat Definition

A risk assessment can be made by modeling fragment liberation characteristics. Modeling will include determination of fragment liberation in and out of the rotor plane and the engine case. In parallel, current engine casings will be analyzed to determine penetration mechanisms and physical design properties. Coupling the fragment liberation models and the engine casing analysis leads to prediction of the damage a fragment can cause as a function of its exit path and energy level. Task accomplishment is based on the use of existing finite element codes. Specialized models will only be developed if required.

After the fragment models are defined, a risk assessment for the aircraft will be conducted. This analysis will determine the risk and probability of a critical aircraft system becoming damaged if a fragment is liberated from the engine. The FAA Technical Center has developed a methodology for rotorcraft and fixed wing aircraft risk assessment. Geometric risk assessments of flight critical systems susceptible to the hazards of uncontained turbine engine rotor failures can be conducted for various rotorcraft and fixed wing aircraft designs. Comparative risk analysis for different designs of each flight critical system can then be conducted.

With failure characterization and risk assessment completed, the overall threat of failure can be determined. This program has identified two approaches that can control catastrophic failure. The first, failure mode prevention, is discussed in Section 2.3.2. The second, hazard threat protection, is discussed in Section 2.3.3. Each method has the potential to reduce and possibly eliminate preventable catastrophic failures. There are many variables that affect the probability of engine failure, ranging from bird ingestion to design standards, manufacturing processes, and human factors. Since not all of these variables can be controlled by one approach, both failure mode prevention measures and hazard threat protection measures are pursued in parallel.

2.3.2 Task II: Failure Mode Prevention

The goal of this task is to improve design, manufacturing, inspection, and diagnostic requirements to form the basis of a superior industry standard. Achieving this goal will reduce the probability of a flawed component entering service and increase the probability of detecting flawed components in service.

Component life is an important factor in engine utilization. Each critical component is assigned a design operating life that is less than its safe operating life. Components are

then removed and replaced at prescribed maintenance intervals. If a component develops a problem before achieving its design life, as determined by inspection, it is removed from service as required. The FAA Titanium Rotating Components Review Team Report (*Reference 13*) noted that: "Most engine manufacturers do not have a formal design procedure to account for the adverse affect of metallurgical defects on the safe life of titanium disks. That is, typically once approved by manufacturing inspection, disks are effectively assumed to be defect-free from a design structural analysis standpoint."

Future rotor design standards will show how more durable designs can reduce the probability of structural failure. These standards can then be applied to the manufacturing, quality control, and inspection processes. Manufacturing standards must be improved to reduce faults and improve the probability of fault detection during manufacturing inspection. Designing in fault detection capabilities during engine development is critical. If a manufacturing flaw escapes detection, the risk of an in-flight failure is increased.

Failure mode prevention can be incorporated during the design and operation of a component or rotating system. Typically the design standards that are utilized have been developed from past experience. However, if the design was altered it may incorporate new inspection or manufacturing requirements that had never been used. Once the component or system is in use, the design practices are transferred to the operator with continuing manufacturer product support, e.g., a repair depot, or fault diagnostics and prediction.

Failure diagnostic and prediction systems are needed to determine the mechanical integrity of a component while it is in service. Diagnostic systems monitor trends in parameters such as vibration, temperature, and pressure. Trend analyses indicate when the monitored component is at risk and support the decision for immediate removal or continued operation until the next scheduled removal. Detection and prediction system research is turning toward neural network technology for expert systems and new types of sensors.

The FAA Technical Center is developing a prototype turbine engine diagnostic system based on expert system technology. The prototype will be demonstrated in flight tests. This system will record and analyze turbine engine parameters that will satisfy the information needs of flight crews, flight-line mechanics, overhaul technicians, and the engine's designer. These diagnostic results will lead to improved failure prevention methods in production facilities, overhaul and repair facilities, and on the flight line.

The FAA has evaluated advanced x-ray inspection technology concepts to locate rotating component cracks while an engine is operating. Conceptually, high energy pulsing x-rays are aimed into the engine at different axial positions, as shown in *Figure 2.5.* To locate a crack, the x-rays are synchronized with the phase angle of the rotating component. This technique can be used to image the interior of an operating gas turbine engine while it is subjected to the heat and centrifugal forces that may cause cracks to open. These cracks may be difficult to find in a static inspection since they may close in the absence of operational heat and centrifugal forces.

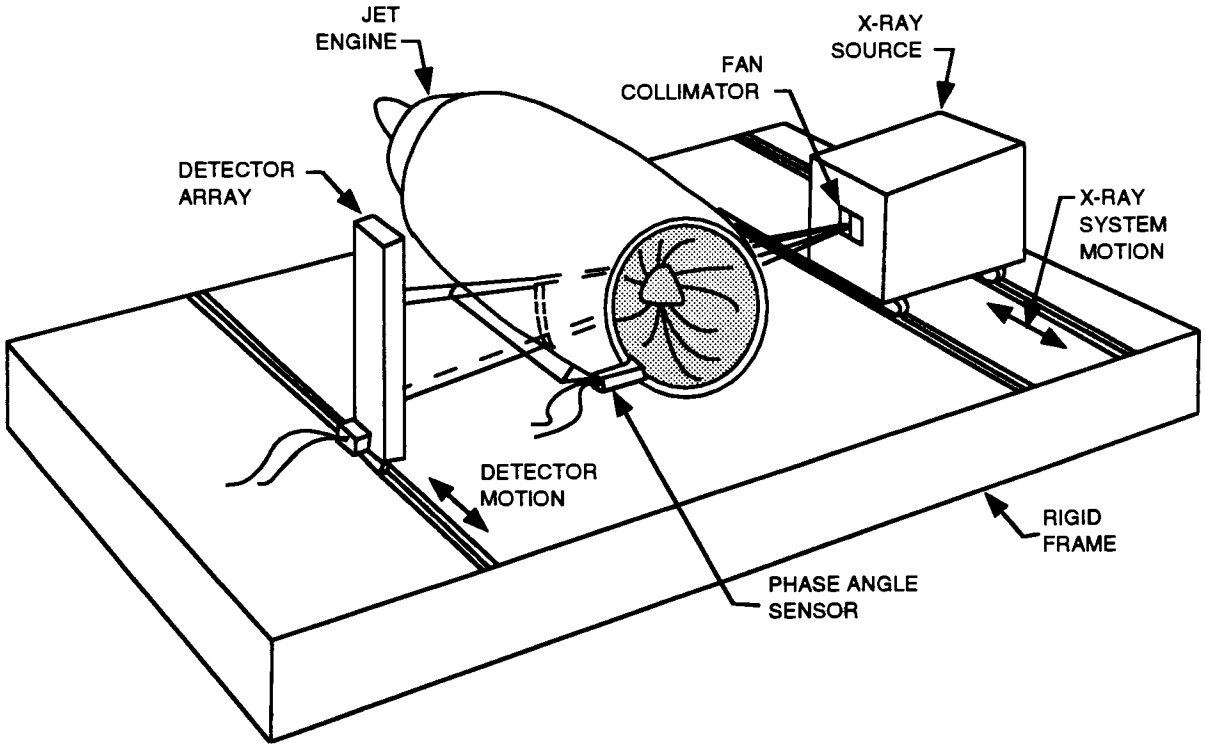

Figure 2.5: Spin Synchronous X-Ray Sinography System Configuration

2.3.3 Task III: Hazard Threat Protection

The goal of this task is to develop the analytical models needed to describe and evaluate the effectiveness of containment/shielding materials and systems for hazard protection from engine fragment liberation. The models will be used to determine the barrier performance needed to achieve the desired level of safety. With this definition of required performance, the effectiveness of existing materials can be evaluated. Results of these evaluations will be a powerful force in guiding future research in advanced materials. As the material technology for barrier use matures, it can be applied to turbine engine rotor case containment and airframe shielding.

Because of the high energy level of an operating gas turbine engine, and the contribution to failure of uncontrolled external variables, the aviation industry believes that absolute prevention of all rotating part failures is beyond the current state-of-the-art.

The SAE obtained turbine engine failure data and prepared AIR 4003 (*Reference 12*) to update its previous study (AIR 1537) of aircraft gas turbine engine noncontainment. AIR 4003 reported 315 uncontained rotor failures for commercial, general, and rotorcraft aviation from January 1976 through December 1983. The SAE data must be viewed within the context of current safety regulations, i.e., regulations for commercial and general aviation require rotor integrity and blade containment but do not address containment of failed disks. AIR 4003 shows that, for commercial transport aircraft, 52 percent of the total uncontained failures that caused significant and severe aircraft damage were caused by disks; 2 percent were caused by fan blades. For general aviation, no severe aircraft damage was reported. However, there were five incidents of significant aircraft damage. Two incidents were due to turbine blades and three were from turbine disks. In the rotorcraft category, 93 percent of the total number of disk and spacer uncontained failures resulted in significant and severe aircraft damage. Blades accounted for three percent of these failures. This data shows that disk failure is a significant threat and that blade containment has had limited success. AIR 4003 reports that rotorcraft have the highest rate of uncontained failures. The use of engine case containment or airframe protective shielding for twin engine commercial rotorcraft may be effective because the turboshaft engine rotors used in these aircraft have relatively low energies. As engines become more powerful, the risk of severe damage increases because the rotors are larger and they have high rotational energies. Advanced design and material research for rotor disk components may reduce mass and size thereby making complete disk containment more attainable.

Over the past decade, there has been a limited amount of turbine engine containment research conducted by government and industry. Most of the research had been focused on blade containment. However, during this same period, substantial advances have been made in light weight ballistic armor material technology. These materials include composites, fabrics, ceramics, metal alloys, and hybrid combinations. Clearly, these new materials should be evaluated to determine their effectiveness in containing fragments.

FAA sponsored programs by DoD and industry are evaluating barrier materials at the Naval Air Warfare Center, Aircraft Division (NAWCAD), Trenton, NJ, rotor spin facility (*Figure 2.6*). Organic matrix composites and ceramic-based materials are being tested in the NAWCAD facility. Future programs will determine barrier material configurations

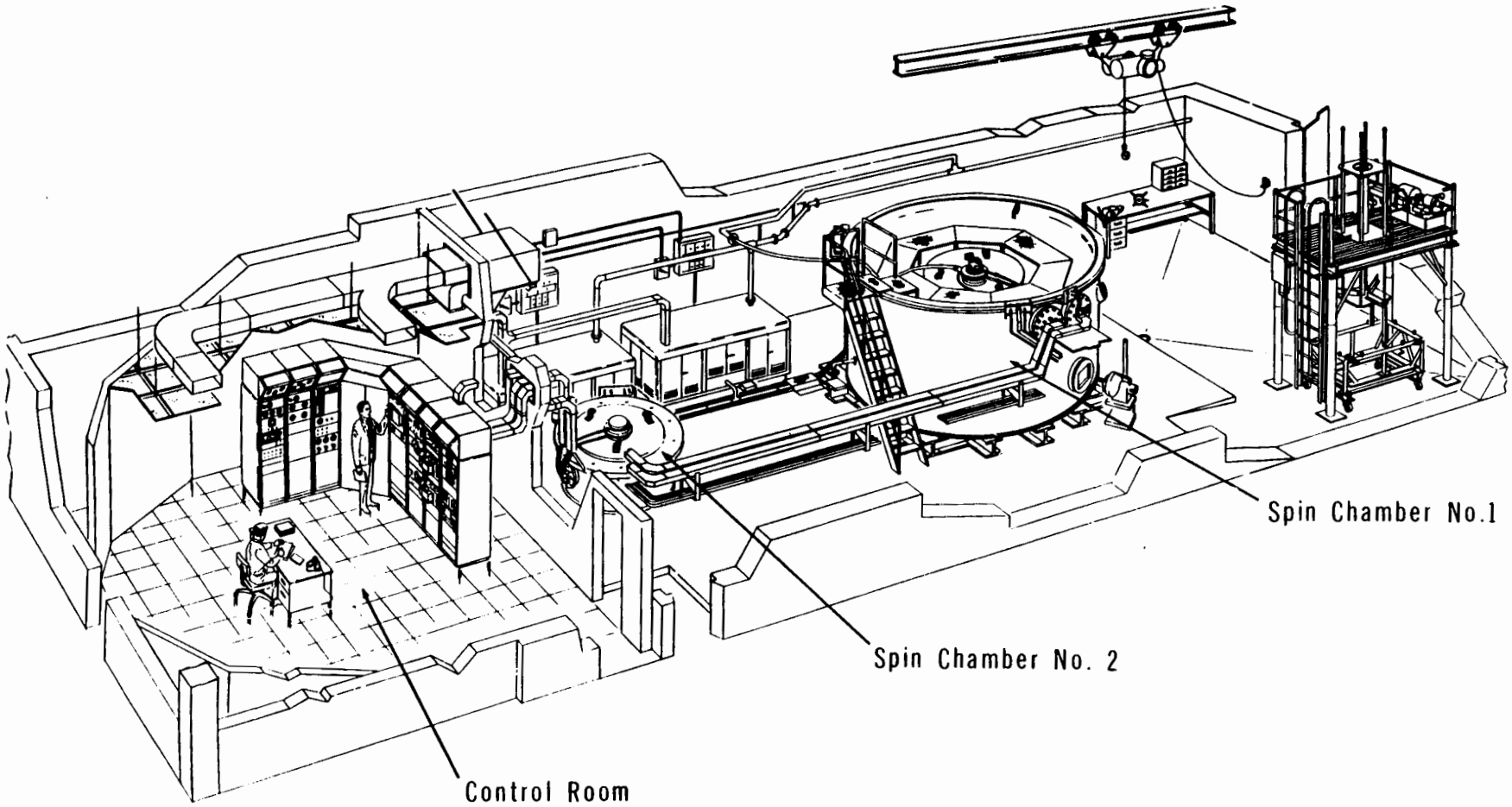

Figure 2.6: Rotor Spin Facility Schematic

and elevated temperature containment structure limitations. To date, these efforts have focused on small turbine engine component fragment threats produced by turboshaft turbine rotors.

Rotor spin facilities are a popular, cost effective, component level test vehicle used by engine manufacturers to support component life determination and the containment performance of the engine case/nacelle against the single blade threat. While these facilities will continue being used to evaluate and develop advanced materials as barriers against the rotor fragment hazard threat, the results may not be applicable to the full-scale engine burst threat hazard. Because the configuration of rotor spin facilities does not duplicate the engine rotor shaft bearing load path of an operating engine, they may not generate realistic rotor fragment trajectories, particularly outside the engine case and nacelle. The vertical shaft orientation of the spin facility also make it very difficult to observe the fragment characteristics and threat outside the engine casing.

Fragment characterization data necessary to define the threat to the airframe structure or systems is required to complete failure risk assessments, computational model validation(s), damage tolerance and barrier/shielding development. This data will be obtained from incident/accident analysis, hardware development testing, and research test facilities as required.

2.4 TASK SUMMARIES

Task I: **FAILURE CHARACTERIZATION, RISK ASSESSMENT, AND FAILURE THREAT DEFINITION**

Approach:
- Determine the failure characterization of critical gas turbine engine components from analyses, independent testing, and incident and accident reports.
- Develop risk assessment methodologies for all categories of failure.
- Define the failure threat.

Importance: Provide risk assessment analysis tools.

Supporting Resources: Universities, Industry, DoD, NASA, and National Labs

Technical Risk: Moderate

Deliverables/Date:
- Risk Assessment Analysis Codes: 1995
- Improved Hazard Design Standards: 1996

Task II: **FAILURE MODE PREVENTION**

Approach: Determine improved methods of preventing component or rotor system faults that may lead to catastrophic failure.

Importance: Improved methods of engine failure prevention will reduce the incidences of a hazardous condition resulting in a catastrophic accident.

Supporting Resources: Industry, DoD, and National Labs

Technical Risk: Moderate

Deliverables/Date:

- Prototype Engine Diagnostic System(s): 1995
- Advanced Quality Control Inspection Tools: 1996
- Improved Rotor System Design Standards: 1998
- Advanced Rotor System Manufacturing Standards: 1999

Task III: **HAZARD THREAT PROTECTION**

Approach: Develop advanced material technology for turbine engine containment and aircraft barrier shielding of hazardous engine fragments.

Importance: Flight critical systems must be protected from the possible hazard of uncontained turbine engine fragments.

Supporting Resources: Industry, DoD, and National Labs

Technical Risk: High

Deliverables/Date:

- Fragment Hazard Analysis Codes: 1995
- Airframe Barrier Material Technology: 1996
- Advanced Engine Containment Materials Technology: 1998

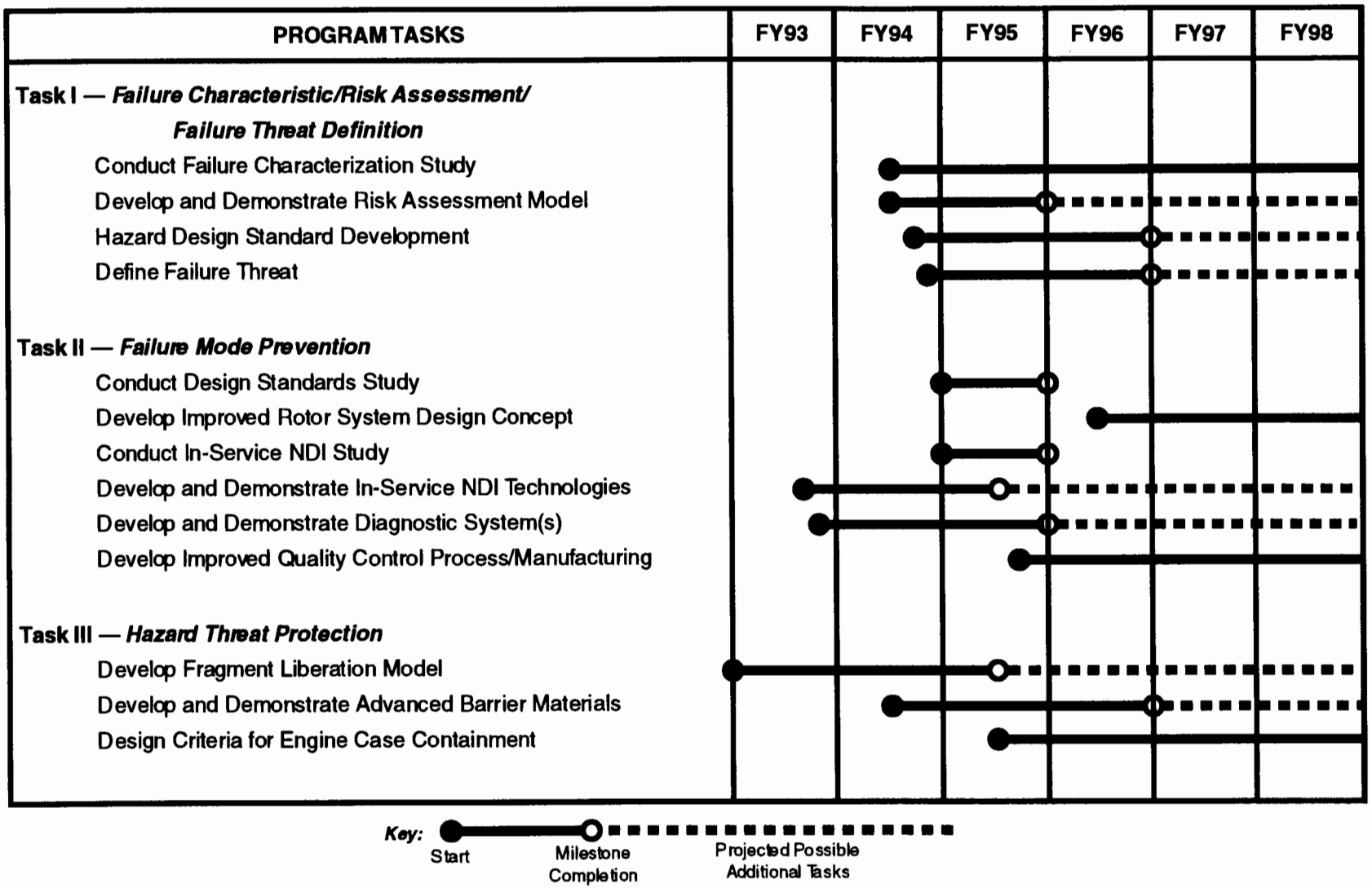

Figure 2.7: Turbine Engine Failure Prevention

3.0 AIRFRAME FAILURE PREVENTION

3.1 INTRODUCTION

The loss of airframe integrity can result in catastrophic failure. Tragic accidents involving the airframe integrity like the loss of a cargo door from a B747 over the Pacific Ocean, an aft pressure bulkhead failure on a B747 shortly after take-off from Tokyo International Airport, the loss of a major portion of the forward-upper fuselage from a B737 in flight and the separation of the left wing engine, pylon assembly and three feet at the wing leading edge from a DC10, during takeoff rotation out of Chicago's O'Hare Airport resulted in a total of 800 fatalities. The FAA has made the prevention of airframe failures a key element of the Aircraft Catastrophic Failure Prevention Program. The goal of the Airframe Failure Prevention Research subprogram is to develop the advanced aircraft design concepts, analysis tools, manufacturing processes, operational monitoring, and maintenance procedures needed to significantly reduce the risk of losing an aircraft due to an airframe failure. Because this research addresses the full life cycle of an aircraft, from design to in-service maintenance, it is applicable to both current and future aircraft (*Figure 3.1*).

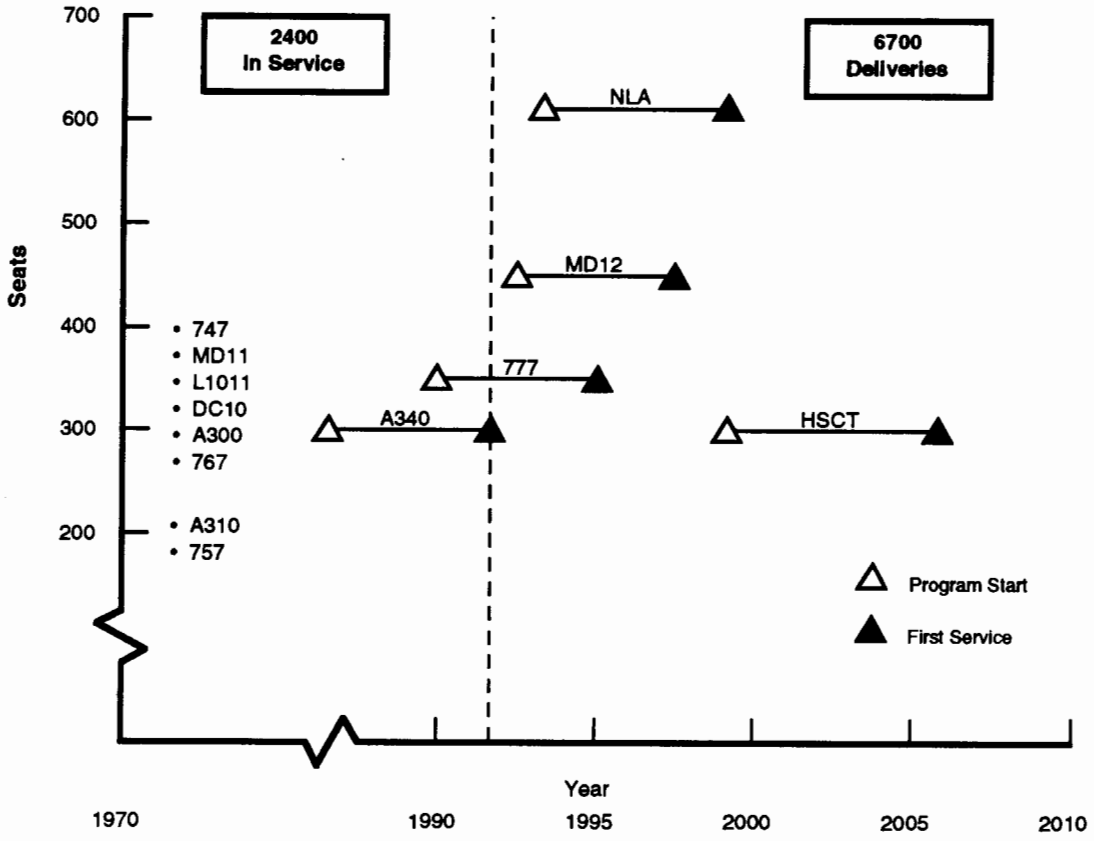

Figure 3.1: Contemporary and Future Commercial Aircraft

3.2 TECHNICAL APPROACH

Figure 3.2 presents a schematic representation of the Airframe Failure Prevention program. The focal point of this research program is the airframe risk assessment. The other activities address preventing or surviving the failure modes identified by the risk assessment. As in other parts of the overall program, technology transfer will be exploited. It is recognized that airframe failure prevention research is now being done in the U.S. for aircraft other then civil transports, e.g., DoD and NASA are doing work in this field for vehicles of interest to them. Outside of the U.S., counterparts of the FAA, DoD, and NASA are also working in these areas. The airframe failure prevention research will seek out those organizations working on this or similar problems and establish the needed paths for technology transfer. This effort will preclude duplication and maximize the value and productivity of FAA supported activities.

3.2.1 Task I Airframe Risk Assessment

Threats to airframe integrity that could result in a catastrophic failure will be defined by this assessment. A listing of airframe failure modes for both current and predictable future aircraft will be developed based on technology transfer workshops, accident reports, and experimental data generated in Task II. These failure modes will include scenarios where the airframe failure may be either a primary or secondary cause of the accident. The likelihood of each failure mode occurring will be determined by using a probabilistic risk model in combination with a fault tree analysis. The failure modes will then be ranked by their likelihood of occurrence. Research tasks will be prioritized by their applicability to the failure modes determined to be the most likely to occur and produce a catastrophic result.

3.2.2 Task II Airframe Failure Mechanisms

One of the main tasks in designing a new aircraft is to predict the structural and external loads that the airframe will experience. Aircraft are subject to many different types of loads which can be the primary factor of some airframe failures. Research conducted within this task will define airframe loads caused by gusts, flight control systems, buffeting, runway slope, normal pressurization, and explosive decompression (*Figure 3.3*).

Gust load criteria for transport aircraft have been developed independently in various countries. In Europe, up until 1979, separate airworthiness criteria were used by the major certifying authorities. Even after the adoption of the European Joint Airworthiness

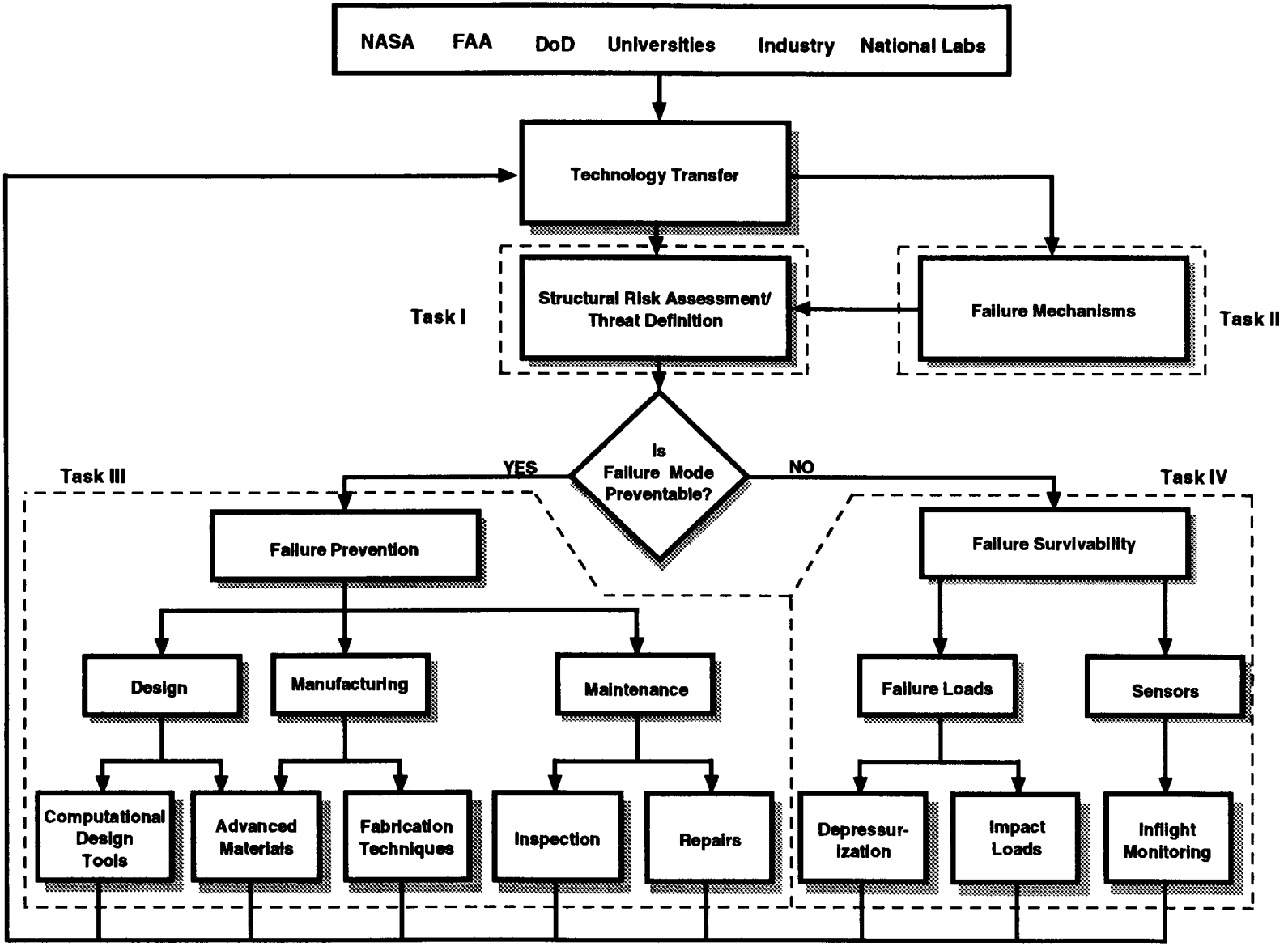

Figure 3.2: Airframe Failure Prevention — Flow Chart

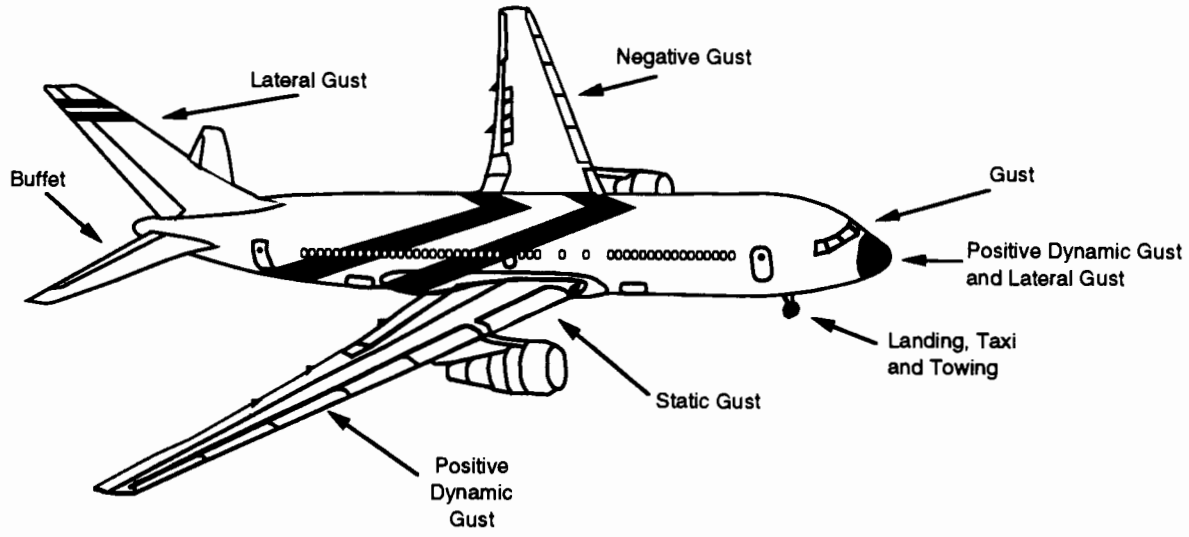

Figure 3.3: Aircraft Loads

requirements for Transports (JAR-25), the member countries were allowed to add their own "National Variants" to the basic code. The net result was that to certify a transport aircraft in accordance with FAR-25 and JAR-25, a manufacturer had to perform seven separate gust analyses, and then design to the most critical loads. An international committee has been working to reduce the number of criteria to be met and to address new technologies such as active controls and load alleviation.

The FAA is moving towards adoption of new gust criteria identical to those recently incorporated in JAR-25. However, the JAR-25 criteria must first be evaluated for current U.S. transports and compared with existing regulations. Dynamic gust analysis will be performed using both the JAR-25 Tuned Discrete Gust Method and the FAR Gust Load Formula in FAR Part 25.341. Results of the two analyses will determine how the JAR-25 Tuned Discrete Gust Method compares to current U.S. requirements.

The use of digital fly-by-wire (DFBW) flight control systems on new generation commercial transport aircraft may result in load profiles not experienced by non-DFBW aircraft. The DFBW-unique flight loads are not well defined. DFBW aircraft may contain logic that will cause control surfaces to move rapidly outside the flight envelope. Also, inflight failure of the DFBW could command rapid changes in the aircraft's control surface positions and result in an unusually high airframe loading. These and other loading scenarios will be studied to ensure that DFBW use in transport aircraft does not increase the chances of catastrophic airframe failures.

Buffet loads can cause large amplitude anti-symmetric rocking motion of the horizontal stabilizer. This phenomenon can occur when the horizontal stabilizer enters the

separated wake behind the wing in conditions such as high angle of attack, with flaps up or down, and landing roll-out with spoilers deployed. The magnitude of buffet loads cannot now be directly calculated. In some cases, buffet loads appear to equal design loads. This was confirmed by flight tests of several commercial transports. For future aircraft to be designed for buffet loads, research must be done to develop methods which can accurately predict horizontal stabilizer design anti-symmetric buffet loads using data available prior to full scale flight test. In addition, research will be conducted to identify flight and ground conditions under which horizontal stabilizer anti-symmetric buffet loads can occur.

Recently, the Aviation Registry of the Commonwealth of Independent States (CIS) suggested that the current FAA/JAA requirements for landing impact may not be satisfactory for CIS airplanes. A significant difference exists between the CIS and FAA/JAA design landing velocities. FAA/JAA criteria require a 10 ft/sec descent velocity onto a flat runway while the CIS criteria require a 15 ft/sec sink speed. The many years of U.S. and European experience using 10 ft/sec alone on civil aircraft has resulted in a rugged, safe, and reliable service worldwide. However, the CIS have indicated that their aircraft and pilots have different performance standards. A minimum of one survey of U.S. and CIS airplanes landing at a common European airport will be conducted to measure and characterize the extent of differences between the landing sinking speeds, approach velocities, etc. between U.S. and CIS aircraft.

3.2.3 Task III Airframe Failure Prevention

Current FAA aircraft safety programs include extensive research to prevent airframe failures in aging aircraft built of conventional metallic materials *(Reference 14)* or advanced metallic and composite materials *(Reference 15)*. The research is focused on operational and maintenance issues specific to the specified materials. The airframe failure prevention research differs in that it is oriented toward multiple and cascading material failures associated with both current and future aircraft designs. The progressive nature of this program allows it to conduct research in a wider range of areas than the existing aircraft safety programs. Therefore, research aimed at preventing failure modes identified by the airframe risk assessment will address the areas of design and manufacturing in addition to maintenance.

Airframe designers are increasing the use of composite material systems and advanced metal alloys to produce lightweight, high strength structural components. New generation materials are slowly finding their way into primary structures from secondary aircraft structures. For example, *Figure 3.4* shows composite utilization on the B777.

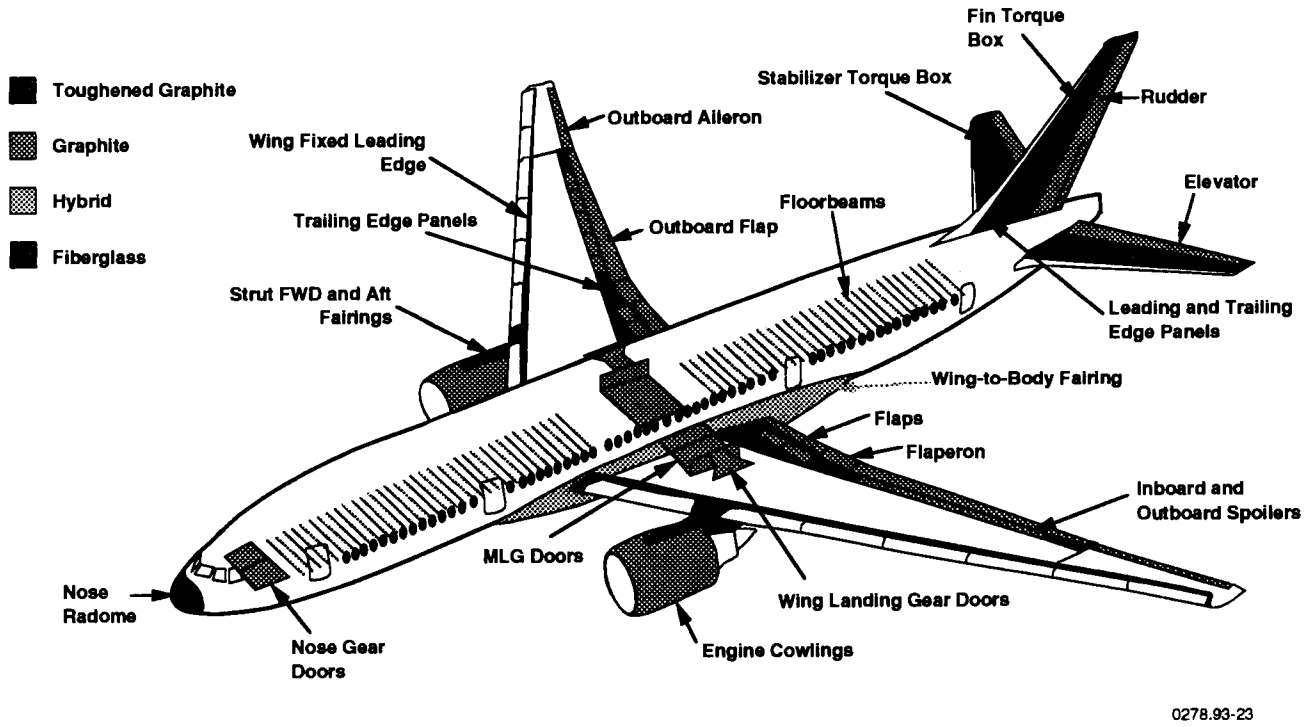

Figure 3.4: Composite Utilization in Pre-Production Boeing 777

As advanced material use increases, it is essential that designers understand the mechanisms by which defects and damage occurs and propagates in these materials. The current body of knowledge developed for design, failure analysis, and repair of metal primary structure transports cannot be applied to composite material systems. Research must be conducted to develop the computational tools needed to model damage formation and growth, and its effects on systems in aircraft constructed of these materials. These models will provide designers with the ability to assess the effects of various damage levels on airworthiness. This predictive ability is also needed to establish supportability criteria using a damage tolerance philosophy and to design airframes with energy absorbing capabilities.

In addition to difficulties encountered in the design stage, new material systems present problems in manufacturing aircraft. The joints in metallic aircraft commonly use rivets to transfer loads between the structural elements. Experience shows that riveted composite joints perform poorly. An alternative to riveted joints is adhesive bonding. Research will be conducted to develop failure trends for adhesively bonded structures. The primary focus of this work will be development of the failure analysis techniques needed to identify adhesives possessing the necessary shear strength and the ability to withstand degradation due to environmental factors.

Maintenance of aircraft constructed from advanced materials will also be investigated. The essential components of a maintenance program are inspection and repair. The role of inspection is the detection of airframe damage before it becomes critical. Non-Destructive Inspection (NDI) research being conducted by the FAA is aimed at detecting damage such as fatigue cracks and corrosion associated with current metallic structures (*Reference 14*) and toward detecting flaws and weak strength bonds in structures constructed of current polymer matrix materials (*Reference 15*).

The Airframe Failure Prevention Research subprogram, in response to the increasing use of advanced metallic and composite materials, will support the NDI research needed to develop technologies and techniques to detect failure modes in structures constructed of these advanced materials. The research conducted will build upon the work carried out by other FAA programs (*Reference 14 and 15*), particularly under-strength bonds. Some of the NDI techniques expected to be of use when applied to the problem of composite damage include advanced ultrasonics, shearography, and thermography. Another valuable source of NDI information is the FAA Aviation Security Program (*Reference 16*). Techniques such as X-Ray Backscatter Sensing and Neutron Activation Sensors developed in the Security Program to detect explosives may be applied in the assessment of composite material damage.

Once airframe damage is detected, the operator must assess the extent of the damage and select the most effective type of repair. The FAA is currently investigating repair issues for both metallic structures (*Reference 14),* and the current generation of composite structures *(Reference 15).* This investigation will assess developments made under other research programs prior to initiating any major research activities relating to repairs.

3.2.4 Task IV Airframe Failure Survivability

The Task III research is aimed at preventing airframe failures by improving the design, manufacturing, and maintenance of aircraft. However, while total prevention of failure is a laudable goal it is not a realistic one. Therefore, Task IV research is directed at surviving those failures which can not be prevented. This task includes efforts to improve aircraft response to unanticipated loads and the development of inflight airframe integrity monitoring systems.

Unanticipated loads include those which are not expected to occur during normal operation, e.g., impact loads resulting from an engine failure liberating fragments into the airframe, collision with external bodies either in the air or on the ground, uncommanded thrust reverser efflux loads, and the structural loads due to rapid

depressurization. Unanticipated loads occurring outside of the design envelope of the airframe may lead to airframe failure.

This research will address the use of advanced materials and innovative designs to increase airframe survivability. Of primary concern will be the development of materials and designs capable of locally dissipating the high energy levels encountered in impact events.

Rapid depressurization at altitude can be triggered by an airframe failure. In certain situations, it is the rapid depressurization that leads to the catastrophic event and not the initial airframe failure. While it is known that rapid depressurization dynamically loads critical airframe structures, there is little quantitative data in this area. It is believed that the quantitative data base can be expanded by reexamination of testing recently done by the FAA which detonated explosives inside a pressurized aircraft (*Reference 17*). These tests, done to determine the effects of terrorist acts on civil aircraft, may provide a base on which the mechanics of rapid decompression can be modeled. Airframe failures at various locations can then be modeled to define those structures that are critical to maintaining integrity during depressurization. With the model serving as a design tool, innovative techniques to control pressure transients and new design concepts for critical structures can be analyzed, and promising concepts can be tested.

If a failure does occur, it is crucial that the crew know the extent of airframe integrity degradation. At present, this can only be done by visual inspection and even that is not always possible. A promising alternative to visual inspection is the use of "smart structures" which monitor their own integrity. If there is an in-flight loss of airframe integrity, the crew would be alerted to it by an on-board computer. Based upon the accurate information provided by the smart structure, the crew could take appropriate action to proceed to a safe landing. Crew action would depend on problem severity and could range from emergency descent and landing to simply notifying maintenance personnel of damage to be repaired.

The equipment necessary to implement a smart structure system includes a network of sensors distributed throughout the aircraft. Sensor output is sent to an on-board computer for processing. An anomaly in the sensor data would be detected and analyzed by the computer and reported to the crew. The primary technological challenge presented by this system is the placement of the sensors throughout the aircraft. Research in this area is now focused on embedding fiber optic and piezoelectric sensors into the aircraft skin (*See Figure 3.5)*. A similar system, known as Aircraft Command in Emergency Situations (ACES), was evaluated by the FAA for use

in cabin fire safety surveillance (*Reference 2*). The ACES sensors monitor the presence of fire and smoke and are different from those which would be used to measure structural response. However, the on-board reporting concepts are similar for fire and structural monitoring. Both types of systems could be integrated into a single on-board computer.

Skin deep, smart sensors may blanket future aircraft to detect and isolate internal structural damage characteristics

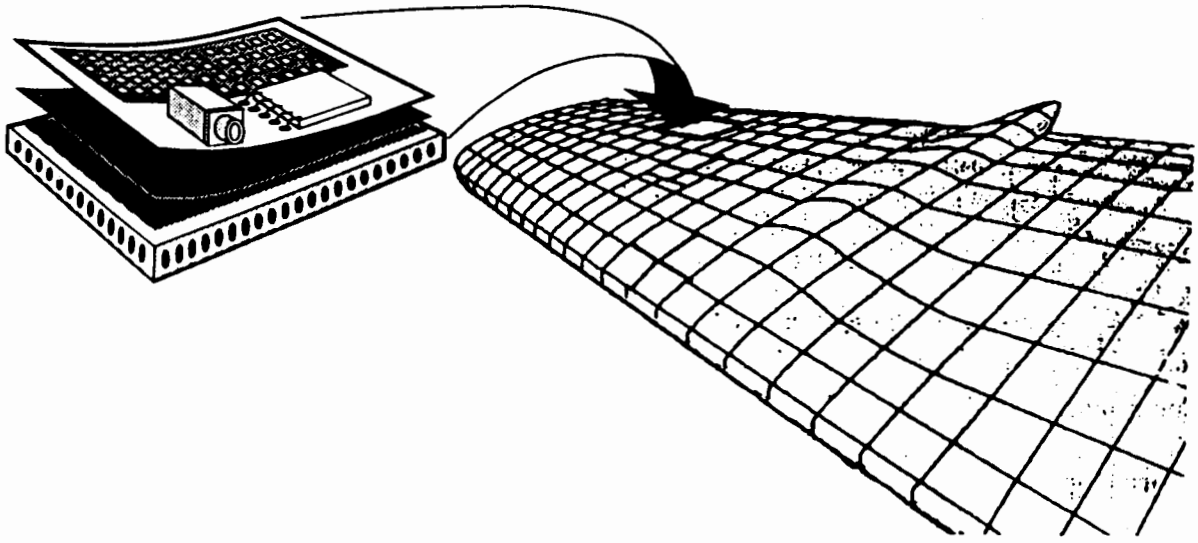

Figure 3.5: Smart Structure Concept

3.3 TASK SUMMARIES

Task I: **AIRFRAME RISK ASSESSMENT**

Approach: Determine likely airframe failure modes by performing a risk assessment.

Importance: Failure modes having the highest risk will be identified.

Supporting Resources: FAA, NASA, DoD, Industry, Universities, and National Labs

Technical Risk: Low

Deliverables/ Date:

- Risk Assessment Report: 1995
- Risk Analysis Software: 1995

Task II:	**AIRFRAME FAILURE MECHANISMS**
Approach:	Gather airframe loads data.
Importance:	Measure loads which can contribute to the failure of an airframe.
Supporting Resources:	FAA, NASA, DoD, Industry, and National Labs
Technical Risk:	Low
Deliverables/ Date:	• Gust Loads Report: 1996 • Buffet Loads Report: 1996 • Landing Impact Report: 1996 • Electronic Flight Control Effects Reports: 1998

Task III:	**AIRFRAME FAILURE PREVENTION**
Approach:	Produce airframes using a damage tolerance philosophy.
Importance:	Prevent airframe failures identified by *Task I* through the development of improved design, manufacturing and maintenance techniques.
Supporting Resources:	FAA, NASA, DoD, Industry, Universities, and National Labs
Technical Risk:	Moderate
Deliverables/ Date:	• Airframe Damage Analysis Software: 1996 • Improved Joint Adhesion Techniques: 1996 • NDI Techniques for Advanced Materials: 1997 • Repair Techniques for Advanced Materials: 1997

Task IV:	**AIRFRAME FAILURE SURVIVABILITY**
Approach:	Address the ability of an airframe to sustain an inflight failure.
Importance:	Increase the aircraft's ability to land safely after suffering an inflight airframe failure.
Supporting Resources:	FAA, NASA, DoD, Industry, Universities, and National Labs
Technical Risk:	High
Deliverables/ Date:	• Computational Impact Model: 1996 • Computational Depressurization Model: 1996 • "Smart Structure" Prototype: 1998

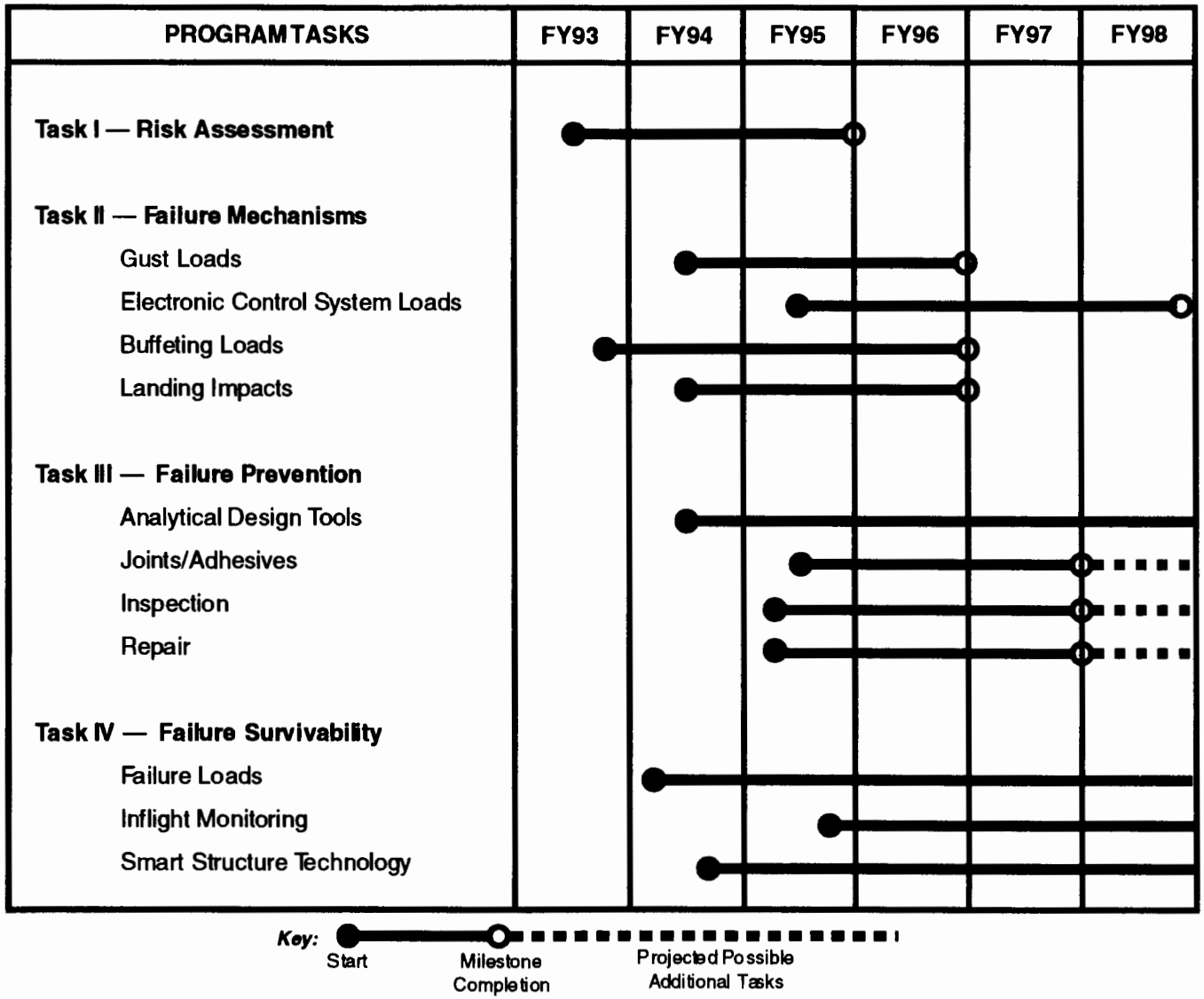

Figure 3.6: Airframe Failure Prevention

4.0 FLIGHT CONTROL SYSTEMS FAILURE PREVENTION

4.1 INTRODUCTION

Flight control system (FCS) malfunctions are of concern in any phase of flight. The inability to precisely control an aircraft, even for an instant, is totally unacceptable. Aircraft accident statistics clearly indicate that loss of flight control, due to equipment malfunction or pilot error, is a major cause of aircraft occupant fatalities (*Reference 18*). Therefore, the goal of this program is to prevent a loss of flight control which could result in a catastrophic situation. The objective of this section is to define the research to be conducted to preclude that catastrophic FCS problem.

The moveable aerodynamic surfaces that are a part of the flight control system and the adjunct systems which operate them, e.g., hydraulic boost devices, are both critical and complex. *Figure 4.1* illustrates the flight control surface configuration and layout for a typical large transport category aircraft. The requirement for continued safe FCS performance is applied equally to aircraft which use mechanically connected, or CONVENTIONAL, control systems and those which use computer controlled digital fly-by-wire (DFBW) or fly-by-light (DFBL) systems.

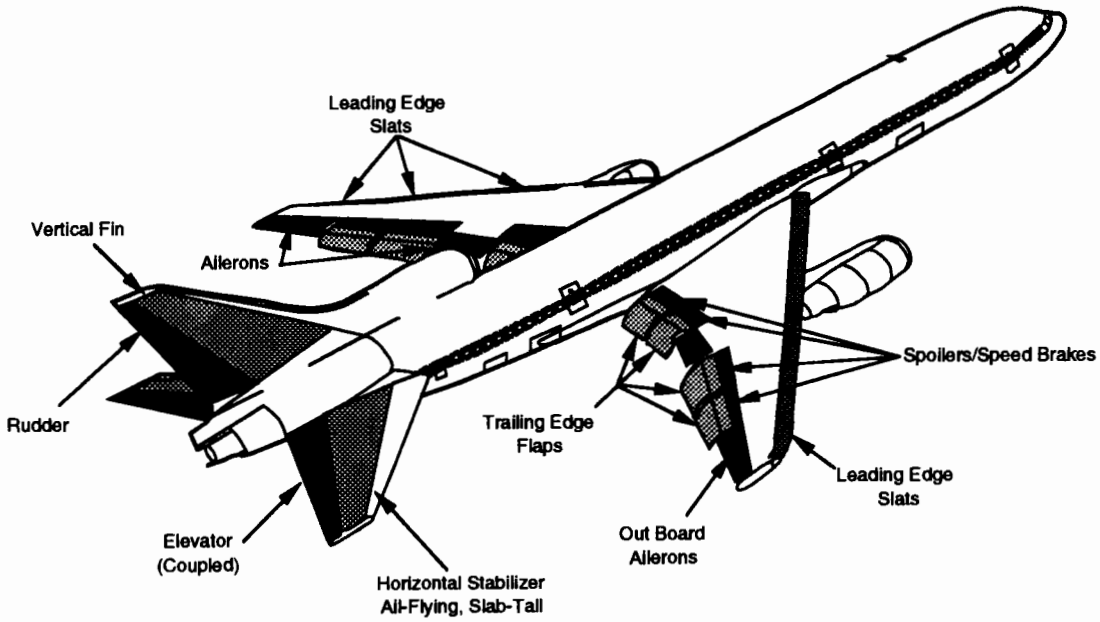

Figure 4.1: Typical Airliner Flight Control Surface Configuration and Layout

4.2 BACKGROUND

Several accidents resulting from a loss of flight control are described here to highlight the technical areas which must be considered, the range of causal factors, and the scope of the problem. These few examples concentrate on failed-mode flight controls and a loss of aircraft attitude control.

In July 19, 1989, a United DC10, Flight 232, was enroute from Denver to Philadelphia with 296 occupants on board when the flight crew heard a loud bang (*Reference 1*). The crew determined that they had lost the tail-mounted center engine and they could not control the airplane as it entered a right turn. The aircraft did not respond at all to the "wheel and yoke" inputs. During the forty minutes of flight after loss of the engine, the flight crew was able to regain a small degree of attitude control and navigate the aircraft to Sioux Gateway Airport by modulating the thrust of wing engines one and three. The aircraft's ground track from the time of engine loss to its crash is shown in *Figure 4.2.* The aircraft crashed on the end of a runway and careened into a cornfield. The crash and ensuing fire resulted in 112 fatalities.

On August 12, 1985, a Japan Air Lines B747, Flight 123, suffered an aft pressure bulkhead structural failure shortly after take-off from Tokyo International Airport. The structural failures caused damage to all four hydraulic power systems available for control surface actuation (*Reference 19*). As the hydraulic system became more disabled, the flight crew appeared to attempt to regain some directional control by modulating engine thrust. The approximate ground track of this flight is shown in *Figure 4.3.* After about 30 minutes, attitude and flight path control were totally gone and the aircraft crashed in mountains about 50 miles northwest of Tokyo. The uncontrolled crash resulted in 520 fatalities.

On May 25, 1979, an American Airlines DC10, Flight 191, crashed in an open field about a mile northwest of Chicago-O'Hare Airport. During takeoff rotation and after the pilot was committed to liftoff, the left engine and pylon assembly and about three feet of the left wing leading edge separated from the aircraft and fell to the runway. After separation, flight control was lost due to an asymmetrical wing stall and the aircraft rolling because of an uncommanded retraction of the left wing's outboard leading edge slats and the loss of stall warning and slat disagreement indication systems in the cockpit (*Reference 20*). The loss of flight control caused by the catastrophic separation resulted in 271 fatalities.

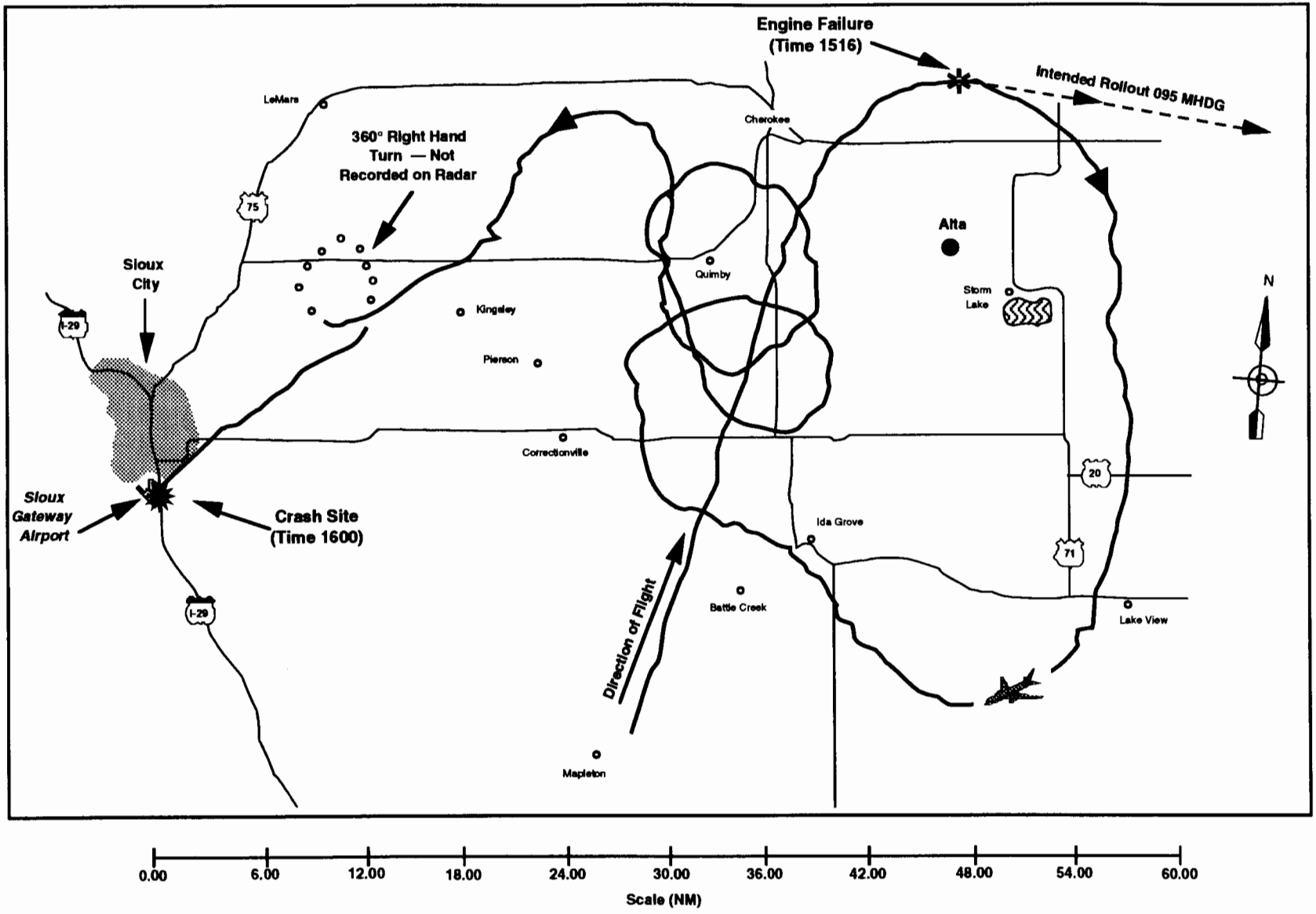

Figure 4.2: Ground Track from Radar Plot of Flight 232

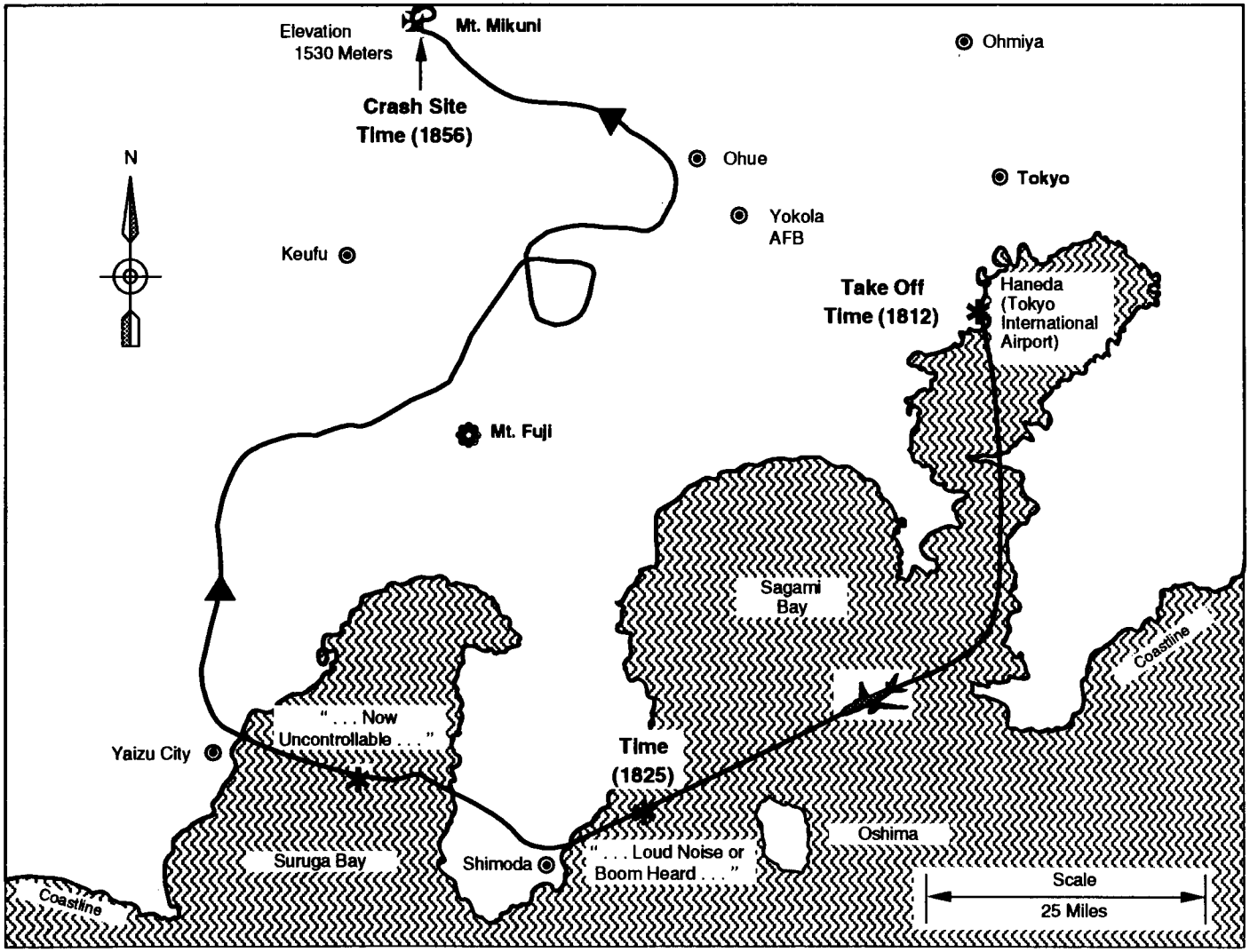

Figure 4.3: Approximate Ground Track for Japan Airlines Flight 123

On May 26, 1991, near Bangkok, Thailand, a Lauda Air B767 flying at altitude experienced an apparent in-flight thrust-reverser deployment. It appears that the aircrew was unable to maintain control due to uncommanded thrust-reverser action on one engine and the aircraft crashed with 223 fatalities.

There are many other examples in which the loss of flight control played a major part in an accident. These examples cover many different types of aircraft, and occur in all phases of flight. The common theme present in many of the examples is that the aircraft was still structurally capable of flight after the failure event but adequate flight control could not be maintained by normal means.

The Systems Review Task Force (SRTF) Executive Summary (*Reference 3*) specifically addresses alternate means of control for aircraft that have lost all normal flight controls yet maintain their basic structural integrity. The document states that its charter is to **"Determine possible design concepts that will provide alternative means of control of flight critical functions in the event of total loss of all (normal) redundant systems which provide that control — regardless of the probability of such loss".** The FAA's position in numerous regulatory documents adds the requirement for **". . . continued safe flight and landing . . . after failures . . . ."**

4.3 TECHNICAL APPROACH

The goal of this effort is to develop and evaluate the means of achieving continued safe flight and landing in the FCS failed-mode scenario. This effort will include the certification process and an operational procedures evaluation. The cost and benefit issues that accompany any new safety system will be addressed.

The technical approach used in FCS research merges engineering disciplines with human factors and behavioral sciences. Well known assessment and testing procedures will also be merged with pilot's subjective ratings of acceptable flight control levels and flying qualities for FCS failures in specified operational scenarios. The final criterion for success is pilot consensus that **"continued safe flight and landing"** can be achieved. The flow chart shown in *Figure 4.4* displays the various task areas and the interactions among the several research disciplines needed to attain the defined goals of the Flight Controls Section of the Catastrophic Failure Prevention Program.

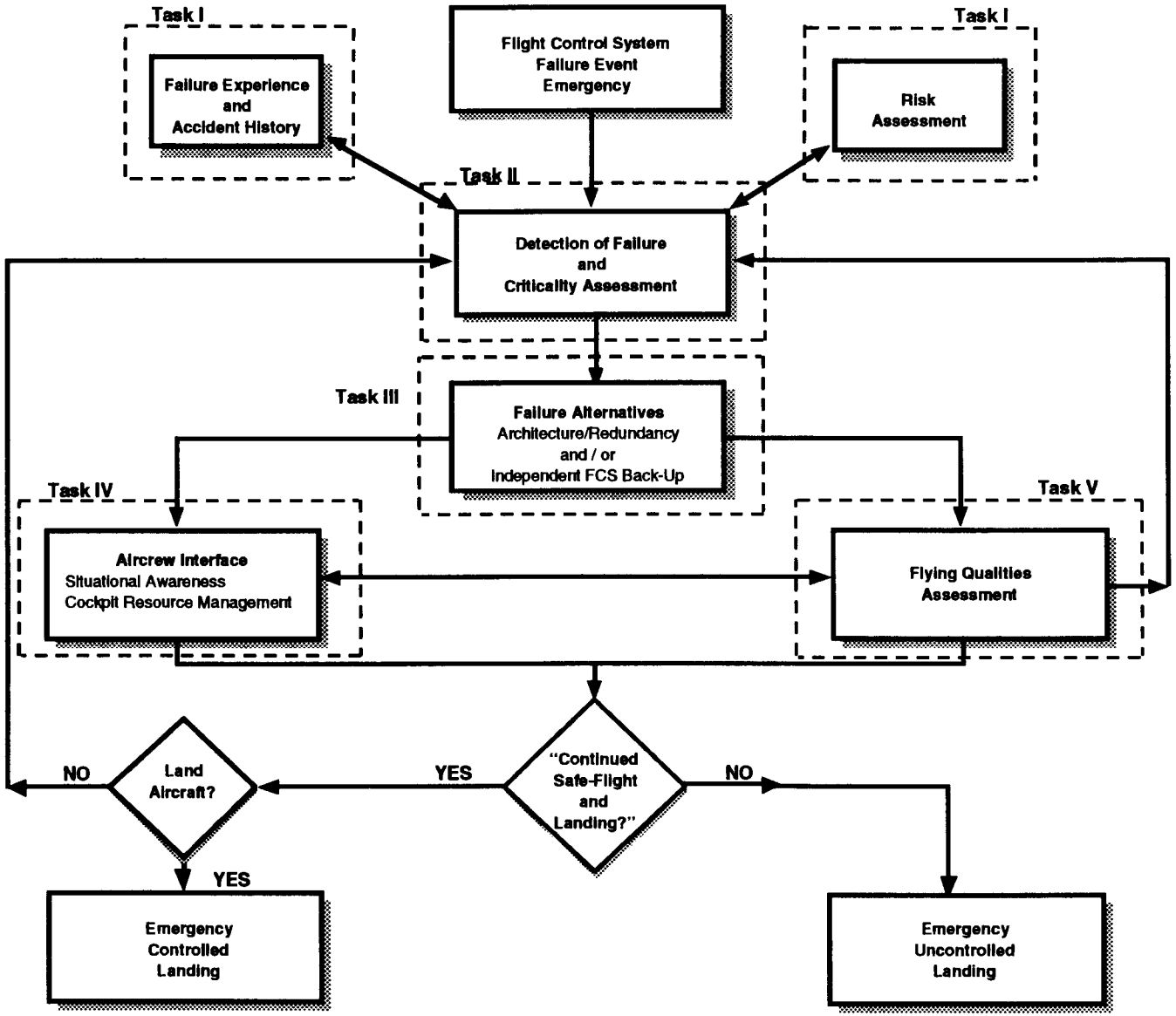

Figure 4.4: Flight Control System Failure Prevention — Flow Chart

4.3.1 Task I: Risk Assessment and Technical Experience

The goal of this work is to develop risk assessment and threat definition information. In part, this will be based on a review of all pertinent accident histories and related safety experience. The review will also serve to validate the scope of research in this program. A comprehensive literature review will collect the past experience and work accomplished in this area. The collected information will be analyzed and interpreted for civil transport application. Some historical material is directly applicable, e.g., the Presidential Task Force on Airplane Controllability established after the DC10 cargo door failure and subsequent passenger floor compression caused flight control failure at Orly, France.

Some work has been done in the failed-mode FCS area by industry and the Department of Defense (DoD). Initial work on Propulsion Controlled Aircraft (PCA) was done by McDonnell Douglas Aerospace for NASA (*References 21 through 27*). There will be extensive interaction with NASA, DoD, other research and regulatory agencies, and industry both here and abroad. Special attention will be given to risk assessment and threat definition information coming from existing FCS research activities.

The risk assessment portion of this task will characterize the severity of failure modes and define the resultant threat level. All internal and external hazard inputs to the flight control system will be analyzed to determine their impact on risk. Single failures with multiple FCS malfunction scenarios will be considered as well as FCS failures initiated by structural failures, uncontained engine failures, and other documented causal actions.

The SRTF established a very broad scope for this work by stating that it was necessary to "Determine . . . alternate means of (flight) control . . . regardless of the probability of such loss." One viewpoint on the relationship between the probability of failure and consequences of failure is shown in *Figure 4.5* (*References 28 and 29*). Another viewpoint cites the requirement, after failure, for ". . . continued safe flight and landing" (*Reference 29*). This risk assessment will define the practical limits and consequences of the research effort. Contemporary risk assessment development procedures, now in use in the aerospace industry, will be used in this study.

4.3.2 Task II: Flight Control System Criticality

The goal of this effort is to develop criticality assessment and probability of performance information for failed mode FCS flight conditions. This research includes the analysis of

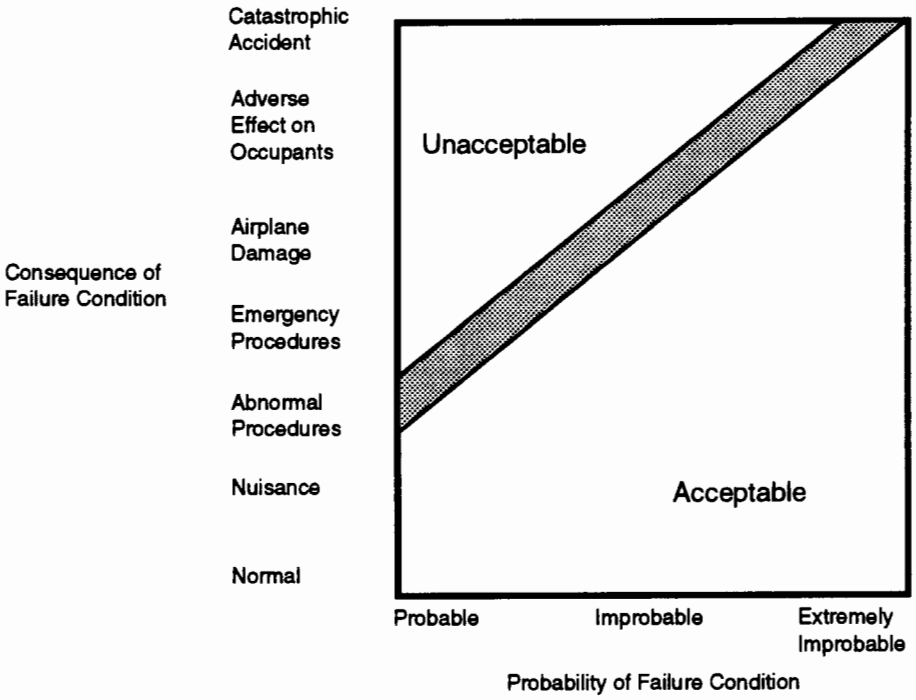

Figure 4.5: Probability vs. Consequence Graph

extremely improbable events, determining the impact of regulations and flight-test techniques on failed mode operations, and determining the probability of loss of flight control system function.

A context for this work exists in regulatory documents. Specific sections of FAR Part 25 and Advisory Circular No. 25.1309-1A, discuss critical functions and probability of the occurrence of failure. The documents define critical functions as those whose failure would contribute to or cause a failure condition which would prevent the continued safe flight and landing of the aircraft. The documents also explain that failure conditions which result from improper accomplishment or loss of critical functions must be "extremely improbable". Extremely improbable events are defined to be so unlikely that they need not be considered ever to occur, unless engineering judgment requires otherwise. The term, extremely improbable, is defined numerically as one chance of failure in one billion tries (per flight hour), or ten raised to the minus ninth power. Noting the regulatory requirements and recalling recent accidents with damaged but structurally flyable aircraft operating under FCS emergency conditions, any control system failure is unacceptable in practically any catastrophic situation. *Figure 4.6* displays the relationship between level of criticality, its functional definition, and its numerical reliability rate.

LEVEL	DEFINITION	RELIABILITY (Failures/Flight Hour)
Non-Essential	Functions which could not significantly degrade the capability of the airplane or the ability of the flight crew to cope with adverse operating conditions if accomplished improperly or lost. Failure conditions which result in improper accomplishment or loss of non-essential functions may be probable.	Probable $\geq 10^{-5}$
Essential	Functions which would reduce the capability of the airplane or the ability of the flight crew to cope with adverse operating conditions if accomplished improperly or lost. Failure conditions which result in improper accomplishment or loss of essential functions must be improbable.	Improbable $\leq 10^{-5}$ $\geq 10^{-9}$
Critical	Functions which would prevent the continued safe flight and landing of the airplane if not properly accomplished. Failure conditions which result in improper accomplishment or loss of critical functions must be extremely improbable.	Extremely Improbable $\leq 10^{-9}$

Figure 4.6: Flight Criticality Levels

The first part of this task will investigate the probability of critical FCS failure due to "extremely improbable" events, for single failures and multiple malfunctions. It should be noted that the FAA regulatory and guidance documents are safety-oriented and deal with redundancy and reliability issues only as related to the impact of failures on safety. The certification requirement is often stated as meeting certain minimum standards to achieve compliance with "a level of safety" — not minimum safety. In fact, commercial transport flight operations are to be conducted at the highest levels of safety.

The premise for this task is that no single failure or probable combinations of failures shall prevent continued safe flight and landing. Therefore, it will be necessary to review and analyze engineering judgment related to extremely improbable failure rate

classifications, failure characteristics, probability estimates, the impact of "minimize the hazard" criteria, single failures and multiple malfunctions, and other fail-safe rules. This task will address both software and hardware failures. Regardless of redundancy requirements, the significance of failure probability projections must be determined and confidence levels established. Special attention will be given to safety assessment procedures, e.g., fail-safe or fail-operate, for single failure cases for critical software and hardware. It will be necessary to review the entire body of regulatory material and Flight Test Guides on FCS failures. This review will be the basis for updating and explaining the certification requirements for single failures that may lead to multiple malfunctions.

The second part of this task will review existing documents to determine their impact on failed-mode FCS operations. This review will include, but not be limited to, FARs, Flight Test Guides, Service Bulletins, Maintenance and Master Minimum Equipment Lists, Alerts, Maintenance Practices and Procedures. FAA's National Resource Specialists will participate in this review and expand it into other related technical areas, e.g., Zonal Analyses, Turbine Rotor Failure Geometric Risk Assessment Procedures, and Routing/Separation/Isolation guidance material for DFBW and DFBL control system components. Minimum Equipment Lists and airplane FCS configurations will be examined if manual flight without Stability and Control Augmentation Systems (SCAS), at aft center of gravity locations, is a possibility. Manual failed-mode flight dynamics without SCAS must be reviewed to determine probability of failure, exposure time, and the impact of environmental factors and turbulence limitations.

The third part of this task will address a special criticality assessment for total loss of the primary flight control system, as directed by the SRTF charter, i.e., review design implications and analyze the safety impact of worse case scenarios for total loss of the flight critical, redundant, primary control system — regardless of probability of loss of that system.

4.3.3 Task III: Flight Control System Architectures and Alternate and Independent Back-Up Configurations

This task addresses CONVENTIONAL and DFBW system architectures. CONVENTIONAL and DFBW systems differ greatly in their FCS design philosophies and implementation. In a pure CONVENTIONAL system, the pilot's hand controller is connected directly to the control surfaces by a mechanical linkage. In a pure DFBW system, the pilot's hand controller is electronically connected to the flight control system with **no** direct mechanical connections to the control surfaces. In either system, hydraulic or electric actuators are often used to move the flight control surfaces.

Powered actuators are nearly mandatory on transport aircraft due to the magnitude of the control forces.

DFBW architectures present the FAA with many new issues and problems related to flight testing, type certification assessments, operational evaluations, and safety compliance. In part, this is due to the fact that DFBW systems can be easily tailored to include new concepts and design philosophies, e.g., control architectures, novel pilot hand controllers, full-authority high-gain control system components, flight envelope tailoring, maneuver limiting, task tailored control system dynamic responses, angle-of-attack and attitude limiting features, and integrated propulsion and flight surface control. DFBW systems rely on other systems, e.g., hydraulic, electric, and pneumatic devices. The relationship of the DFBW system to mechanical systems must be established. *Figure 4.7* is a schematic of DFBW architecture and component systems for computer commanded pitch attitude control on a current airliner (*Reference 27*).

The objective of this effort is to conduct the research that will provide the data and information needed to prevent accidents after catastrophic failure of the flight control system. Major areas of interest are system design architectures, system redundancy, and back-up/alternate/reconfigurable control systems. This effort will concentrate on the development of testing criteria, assessment procedures, and safety compliance assurance for both CONVENTIONAL and DFBW systems.

A review and analysis of FCS architectures and design philosophies will be conducted within the context of selected failed-mode FCS scenarios. For CONVENTIONAL systems, safety issues will be studied as they relate to mechanical linkage and cable routing, extensible links, boost and stability augmentation devices, trim devices, and related mechanical, electric, electronic, hydraulic, and pneumatic components. Aircraft configuration implications and the impact of isolation, multi-path location, and partitioning of CONVENTIONAL control system components will be analyzed for the failed-mode cases. Parallel efforts will address Stability and Control Augmentation Systems and digital controls, both Fly-By-Wire and Fly-by-Light optical fiber based systems. Control architecture concepts to be covered will include design schemes such as: Duplex; Triplex; Quadraplex; Dual/Dual redundant systems that may be Fail Operational with fault correction, Fail Soft, or Fail Passive with Monitoring, Partitioning, Dissimilarity and Isolation.

The use of each available aerodynamic control surface will be addressed to determine its utility for and contribution to continued safe flight in each failed mode scenario. The use of modulated engine thrust to generate emergency forces and moments for aircraft

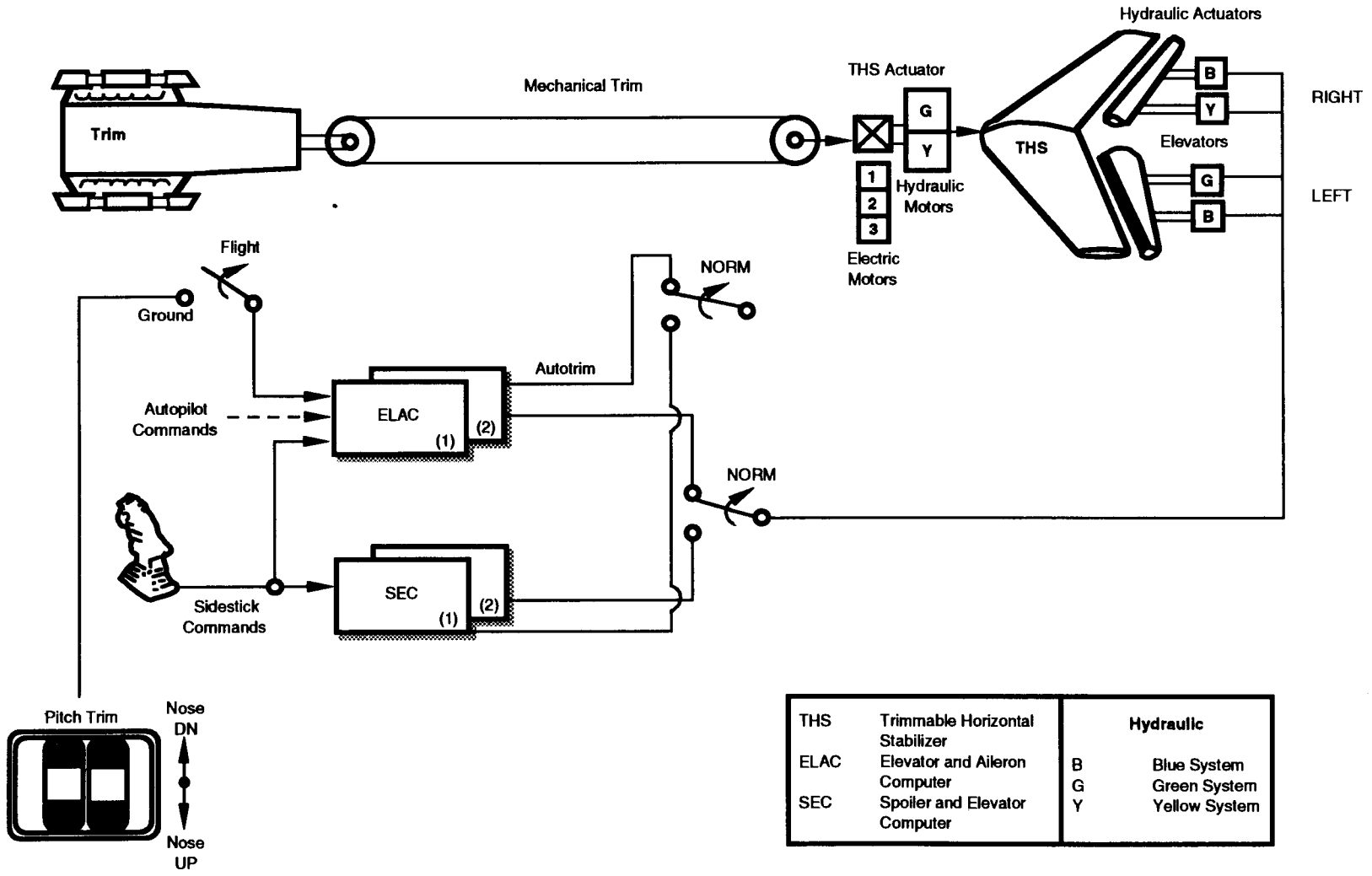

Figure 4.7: Manufacturer's Schematic for Typical Fly-by-Wire Pitch Control (Reference 27)

alternate flight control will be fully investigated. All possible types of in-flight thrust, aerodynamic force, and moment asymmetries will be analyzed to determine their impact on failed mode flight control and continued safe flight and landing. Special consideration will be given to asymmetric flight emergencies where peculiar failure events cause special control situations, e.g., damaged, missing, and inoperative wing leading-edge devices; large thrust asymmetries such as two engines lost on one side; split flap or slat conditions; and uncommanded thrust-reverser or slat operation.

The second part of this task will analyze redundancy levels and reconfigured, alternate, and independent back-up flight control systems. The objective of this part of the task is to develop the data and information that the FAA may use for a more informed technical appraisal process, a more efficient assessment procedure, and an improved safety assurance/compliance system for FCS and redundancy philosophies.

The primary flight control system is a flight critical system whose chance of failure must be classed as "extremely improbable". If there is a failure, the fault tolerance must be such that the flight control system continues to function in a satisfactory fashion in the presence of the failures. High levels of fault tolerant operation are usually achieved by redundancy. Highly reliable and redundant DFBW systems are designed to have failure rates that are "extremely improbable". It is very difficult to guarantee this level of reliability in the fundamental control architecture and testing, assessing, and proving safety compliance may be even more difficult. Some DFBW architectures suggest that, to guarantee the stated high levels of reliability, they may require the use of adjunct control designs and philosophies such as Independent Back-Up (IBU) systems, alternate controls, reconfigurable controls, trim system alternatives, etc.

4.3.4 Task IV: Aircrew Training, Human Factors and Pilot Interface with Aircraft Flight Control System

The pilot is critical to the resolution of in-flight emergencies. The pilot's interface with the aircraft and its flight control system is critical to any problem resolution. The research needed to analyze that interface draws on technical disciplines and human engineering to explore pilot interaction with automation, advanced electronic displays, and computer managed cockpit environments. It is likely that Human Factors and Aircrew Training for failed-mode operation in a highly automated cockpit will offer substantial safety rewards.

The emergency flight control scenario includes many pilot actions, e.g., fault diagnosis, reasoning, logic, contingency action, decision making, incongruities, prediction,

evaluation and judgement. The objective of this effort will be to review and analyze the past experience and new approaches to human factors and training issues related to the pilot performance in failed-mode FCS flight.

The first part of this task addresses FCS failure detection and aircrew situational awareness issues. A review of the technical literature will be conducted to analyze the impact of different FCS failure detection schemes, aircrew situational awareness, cockpit resource management, human-centered automation, pilot judgment and decision-making, and other human factors issues. A study will be made of the human performance impact of new types of displays, warning systems and cockpit alerts, advanced flight management systems, performance monitoring systems, automated flight control and aircrew duty cycles.

The second part of this task will conduct an analysis of FCS controller mechanisms and their impact on the failed-mode flight condition operations. This task will focus on technical and human factors issues of concern to designers, engineers, human behavioral analysts, pilots, and certification personnel. The analyses will concentrate on hand controller designs that may have a significant impact on the man/machine performance during emergency conditions, e.g., Center Stick, Side-Stick, Wheel and Yoke, Automatic/Coupled Flight, control/command input authority and priority between pilot and copilot using side-sticks, tactile cueing, and "backdriving" of DFBW cockpit primary flight surface hand controllers and engine power levers.

4.3.5 Task V: "Continued Safe Flight and Landing" Flying Qualities Assessment Criteria

As flight control systems become more sophisticated, control input and resulting aircraft dynamics and flight path are no longer tied to familiar conventional dynamic responses. The designer can tailor the system to provide the flying qualities that pilots find highly desirable. With DFBW systems, the pilot's controller input can be modified to provide "optimum" flight responses, as developed by the system designer. The automated optimum flight control response systems are highly redundant and reliable architectures whose failure rates are "extremely improbable". However, most all flight control systems have failed or presented anomalies for a variety of reasons and some have even experienced catastrophic failures.

Without regard to control system architecture, after failure the pilot plays the most significant role in achieving the flight control required for continued safe flight and landing. Therefore, the objective of this effort is to integrate all the research findings of the previous tasks with this subprogram's efforts to generate the best solutions to satisfy

the SRTF's requirements. This research will furnish the information and guidance needed to provide alternate means of critical flight control function even in the event of total loss of all normal redundant systems which provide that control function — regardless of the probability of such loss. The research will assess the problem on a holistic basis while keeping in mind satisfactory pilot workload and minimum acceptable aircraft flying qualities criteria issues for continued safe flight and emergency landing.

The research will provide measured results and list specific requirements that categorize acceptable flying quality ratings needed for "continued safe flight and landing". These requirements and rating levels will provide guidance for flight control designers regarding the viability of various Reconfigured Systems, Independent Back-Up, IBU, or Fault Tolerant system features. The task will determine if IBU features are needed for multiply redundant control system designs.

The flying quality ratings for failed-mode configurations for "continued safe flight and landing" are not the same as the usual flying qualities rating measurements since they may only define minimum level needed for this emergency condition and configuration (*Reference 30*). If the aircraft is to land on the back-up or reconfigured system, the Pilot Rating should determine the minimum value needed specifically for that task. If the task after failure is to maintain initial attitude or regain control, then a lesser Flying Quality Pilot Rating may be acceptable for a temporary period. *Figure 4.8* gives an example of the development of an FAA Flying Qualities (Pilot) Rating method (*Reference 28*).

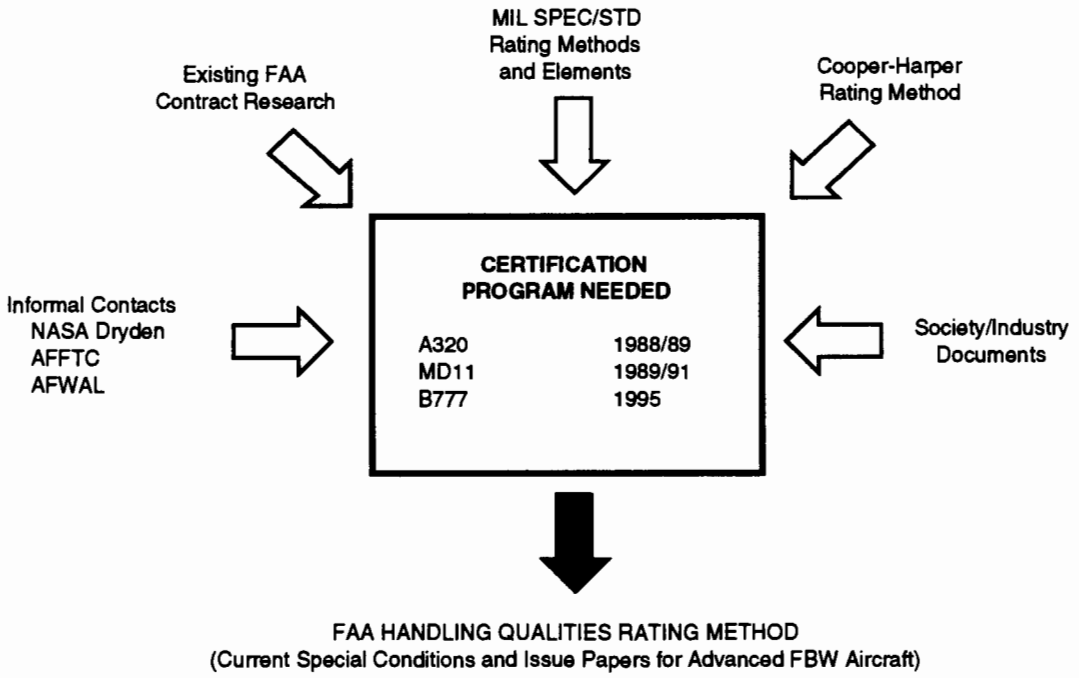

Figure 4.8: Development of FAA Handling Qualities Rating Method (Reference 28)

The research will be based on a complete review and analysis of flying qualities. Existing flying qualities data and specific pilot information, testing procedures, and criteria applicable to non-failed-mode and failed-mode FCS operation will be reviewed and validated. Requirements will be identified for minimum primary and secondary aerodynamic control surface requirements for acceptable controllability, to "minimize" the failure hazards, and to provide for continued safe flight and landing. This work will include defining and analyzing all non-conventional aircraft force and moment flight control generators (e.g., differential/collective engine thrust used in PCA), available to the aircrew for auxiliary controllability under some failed-mode conditions.

The second part of this task will quantify how much failed-mode control is needed as a function of the remaining aircraft stability after the failure. Investigations will cover the base dynamic stability in the failed condition for various levels of static stability and the impact of a failed augmentation system on basic dynamic stability.

The third part of this task is an analysis of Flight Envelope issues. For failed-mode flight, the research will investigate the impact on different predefined flight envelopes. A review will be conducted to evaluate safety issues related to flight envelope design philosophies.

4.4 TASK SUMMARIES

Task I: **RISK ASSESSMENT AND TECHNICAL EXPERIENCE**

Approach: The risk assessment portion will characterize the gravity of the failure modes and define the threat levels.

The accident history and past technical experience portion of this task will establish the limits and the requirements of the section.

Importance: The risk assessment will identify the threat and provide the risk analysis tools.

The technical experience will provide the accident history and review past work.

Supporting Resources: NTSB, AAI, ANM, DoD Safety Offices, NASA Safety Offices, Manufacturers, Foreign Safety Offices, universities and research organizations.

Technical Risk: Moderate

Deliverables/Date:
- Failure modes risk assessment and methodology: 1996
- Accident analyses overviews, and technical interface: 1996

Task II: **FLIGHT CONTROL SYSTEM CRITICALITY**

Approach: Review and analyze all aspects of FCS Criticality, Extremely Improbable Failure Modes, Efforts to "minimize" the hazard, Impact of the regulations and testing, and total loss of the primary control system.

Importance: This work will assess FCS criticality and impact of different failure modes.

Supporting Resources: ANM, NRS, Pertinent Headquarters Offices, Safety Organizations, Manufacturers and Airlines, NASA, NTSB, DoD Safety Offices, universities, research organizations and private industry.

Technical Risk: High

Deliverables/Date:

- Review of criticality and extremely improbable failure analysis: 1996
- Zonal analyses for critical failure issues: 1997
- Total loss of FCS review and analysis: 1997

Task III:	**FLIGHT CONTROL SYSTEM ARCHITECTURES AND INDEPENDENT BACK-UP CONFIGURATIONS**
Approach:	Define and analyze the FCS architectures
Importance:	This work will structure the analysis of the different FCS and provide the tools to assess back-up units.
Supporting Resources:	Aircraft and systems manufacturers, Architecture and systems analysts, Independent Back-up or Fault Tolerant systems designers, NASA, DoD, Simulation Laboratories, universities and other research entities such as Calspan Corporation, NY, and Institute for Flight Guidance of DLR-Germany (ATTAS In-flight Simulator and Ground-based Simulators).
Technical Risk:	High
Deliverables/Date:	• Data and Information on FCS Redundancy and Architectures: 1997 • Impact of IBU Systems: 1997

Task IV: **AIRCREW TRAINING AND PILOT INTERFACE WITH AIRCRAFT FLIGHT CONTROL SYSTEM**

Approach: This task address that facet of the program that directly impacts design, aircrew interface, Human Factors, Pilot Error and crew training issues.

Importance: The work will provide the needed human factors data.

Supporting Resources: Aircraft, equipment and systems manufacturers, test pilots and line pilots, ATA, ALPA, NASA, research organizations and universities, Human Factors laboratories and entities, Psychologists and Human Behavioral experts, engineering organizations, simulation facilities and experts, ANM, NRS, NTSB, DoD, and pertinent foreign entities.

Technical Risk: High

Deliverables/Date:

- Preliminary Failure Detection Analyses: 1997
- Guidelines for CRM, SA, Pilot Judgement/Expert Decision Making: 1997
- Data on Pilot Controller Types: 1998
- Pilot Training Syllabus: 1998.

Task V: **"CONTINUED SAFE FLIGHT AND LANDING" FLYING QUALITIES ASSESSMENT CRITERIA**

Approach: This effort melds and utilizes all the facets of all the previous tasks in this section. It combines the tasks and results of all the previous sections with the tasks of this section in order to obtain holistic and synergistic usable solutions for the overall goals of the total program.

Importance: This work will provide the technical data, flight test information and guidance material, needed by the agency.

Supporting Resources: NASA, DoD, manufacturers and users, NRS, universities, national laboratories, etc.

Technical Risk: High

Deliverables/Date:

- Analyses related to acceptable flying qualities for failed-mode FCS flight and landing: 1997
- Aircraft flight envelope data and information: 1998

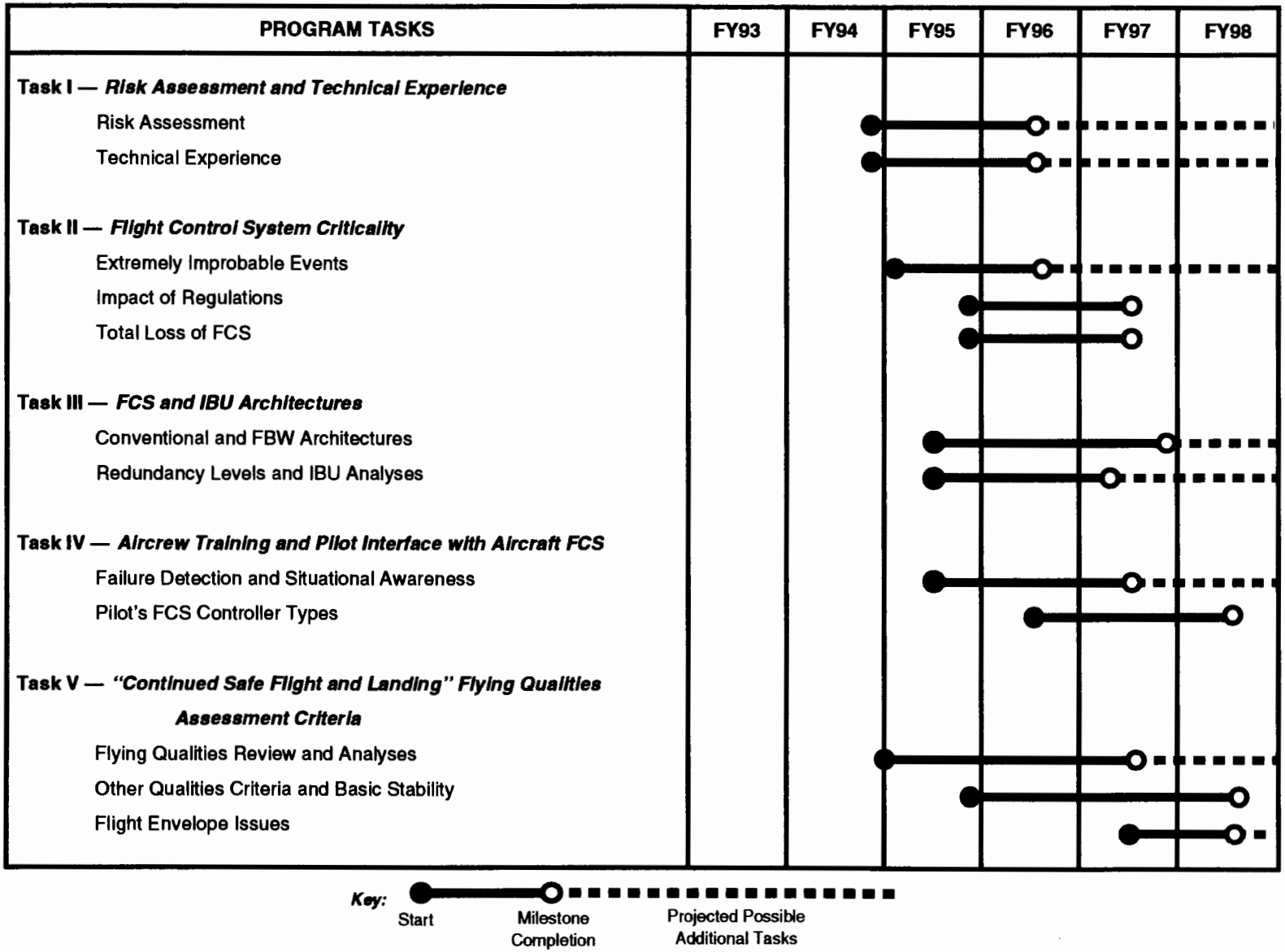

Figure 4.9: Aircraft Flight Control System Failure Prevention

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