CHAPTER 3
EMERGING AVIATION TRENDS: POTENTIAL IMPACT ON AIRCRAFT ACCIDENT INVESTIGATIONS

The nature of NTSB investigations and the agency's future workload will be shaped by changes in the aviation environment, in particular by increasing technological complexity and growth in general and commercial aviation air traffic, and by important changes in the composition of the air transport fleet. The burgeoning popularity of personal use aircraft will also impact the NTSB's workload.

This chapter examines these trends and how the Safety Board's processes are likely to be challenged by technological innovations that are changing both aircraft and the airspace in which they operate. Cumulatively, these technological changes aim to increase reliability throughout the aviation system and vastly improve safety in the skies. These changes include systems designed to move aircraft more efficiently in the air and on the ground, methods for providing pilots and ground controllers with better information about traffic and weather conditions, and improvements in aircraft components and design.

The growth in aircraft system complexity is exponential in many areas, with the most significant trend being the interconnectedness of systems. Current-generation aircraft operate as highly integrated systems with extensive cross-linking. As system complexity grows, so does the concern about hidden design flaws or possible equipment defects.

Accidents involving complex systems and events present investigators with new and different failure modes that multiply the number of potential scenarios they must consider. The historically common causes of accidents are occurring less frequently, leaving more challenging accidents to diagnose. In response, the NTSB must develop new investigative processes and training procedures to meet the challenges that the rapid growth in systems complexity presents.

IMPROVING THE SAFETY AND EFFICIENCY OF AVIATION

The dramatic loss of TWA Flight 800 in 1996 galvanized national concern over aviation safety and gave birth to the WHCASS. A 1997 report from the commission set a *national* goal to reduce the air carrier fatal accident rate by 80 percent within 10 years (Office of the President of the United States, January 1997). NASA also embraced this goal, but set an even more ambitious target--providing the technology to reduce the U.S. accident rate by 90 percent within 20 years (National Aeronautics and Space Administration, 1999). Boeing maintains a corporate goal of working with the aviation community to try to achieve a *worldwide* 50 percent reduction in fatal accidents over the next 10 years (Higgins, June 1998).

A three-agency alliance of the FAA, NASA, and the DOD are engaged in a broadly based joint research and technology development effort to meet the goals stated here.[1] Together, the three agencies are committing more than $3 billion over the next five years to achieve the aviation safety and security goals. NASA alone has pledged to augment its existing aviation safety program budget by $500 million during this period. Federal investment will likely continue at current levels beyond 2002 as the national airspace infrastructure continues to improve and as highly advanced technologies reach maturity and are implemented. These monetary investments have been made with three goals in mind:

- **Reduce accident precursors:** reexamining aircraft systems, ground equipment, operating systems, and procedures to reduce incidents that are known to precede fatal accidents. A significant reduction in the number of precursors should cause a parallel reduction in the likelihood of fatal accidents.

[1]The role of the DOD in contributing to improvements in civil aviation safety is often underestimated. The DOD is the largest operator of aircraft in the world. The combined military services operate a total of 16,300 aircraft. As an air traffic control provider, the DOD and its facilities handled 11 percent of all nationwide air traffic in 1995. This amounted to 18.4 million aircraft, of which 3.7 million were civilian and 14.7 million were military. This experience base, as well as the many research and development initiatives under way to improve military aviation safety, profoundly influences the planning and implementation of civil aviation system improvements.

- **Create inherently safer aviation systems:** focusing on safety in the design of aircraft and aviation systems and the procedures used to operate them. This requires an understanding of how and why accidents occur, including a continuous reinforcement of lessons that have been learned.
- **Design failure-tolerant aircraft:** building systems that can withstand failures or that can maintain a safe environment for aircraft passengers and crew when a failure occurs.

National Aviation Safety Goals

The future demand for NTSB's accident investigation services will be shaped in large part by the success of worldwide efforts to reduce accident rates. Impressive reductions in accident rates have been achieved since the first introduction of jet transports; however, that progress, measured in terms of hull losses per million departures, has tapered off during the last two decades.[2] Simply combining the current global accident rate with traffic growth projections leads to the oft-cited observation that if accident rates are not reduced within about the next 20 years a fatal air carrier accident could occur an average of once a week somewhere in the world (Office of the President of the United States, January 1997). This projection has motivated public and private sectors to develop initiatives to reduce accident rates.

Figure 3.1 shows the range of possible scenarios the NTSB faces in terms of potential domestic major accidents. The projections on the chart illustrate three projected accident trends:

- No change in accident rate (accidents grow in line with traffic growth)
- A 50 percent reduction in the accident rate by 2007
- An 80 percent reduction (20 percent of the 1988–1997 accident rate) by 2007, the Clinton administration's goal.

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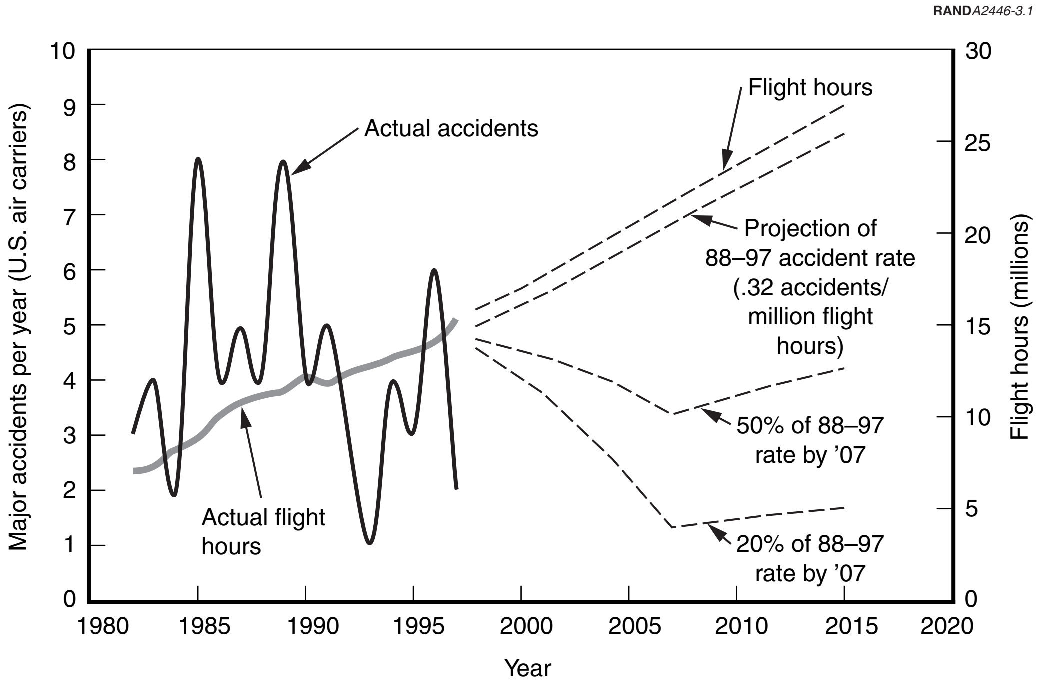
[2]An aircraft accident can be minor or major. A major event does not necessarily cause fatalities. Readers should note that although aviation safety goals target reductions in the fatal accident rates, the NTSB workload is determined by the number of minor and major accidents, not just those accidents that incur fatalities.



SOURCE: Developed from the NTSB Aviation Accident Data Base; FAA Long-range Aviation Forecasts, Fiscal Years 2010, 2015 and 2020, FAA Office of Aviation Policy and Plans, June 1998; FAA Aviation Forecasts Fiscal Years 1997–2008, FAA, March 1997; WHCASS and Boeing Safety Goals.

Figure 3.1--Projected Accident Rate Scenarios

The potential trends range from an appreciable drop to a significant increase in the number of accidents. If the first projected scenario (accidents grow in line with flight hours) becomes a reality, average accidents per year could double within the next 20 years, in all likelihood requiring an increase in NTSB staff.[3] If the accident rate is halved, such as in the second scenario, that reduction will be almost completely offset by the effects of increased traffic, leaving the average number of accidents per year at today's levels. If the third scenario occurs, the accident rate will fall faster than the projected traffic growth, potentially resulting in a net decline in annual U.S. air carrier accidents.

At this point, three years into a 10-year program, it is far too early to consider making staffing adjustments based on an expectation of

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[3]The projections assume a linear transition from the current accident rate to the new accident rate by 2007, although actual accidents would never be expected to occur in such monotonic fashion.

fewer U.S. air carrier accidents in the future. Moreover, focused research and development that leads to a reduction in the number of domestic accidents, however positive, is offset by two important realities:

- First, the nature of aircraft crashes will likely change and the NTSB will face a substantial increase in the complexity of accidents and the level of interest surrounding investigations, particularly in terms of litigation and the intensity of public scrutiny.
- Second, the level of NTSB support to foreign investigations depends on the effectiveness of international safety initiatives. Whereas the U.S. and Canadian accident rate for hull losses and/or fatal accidents is roughly one loss per one million departures, the rate in the rest of the world is three times higher (Boeing Commercial Airplane Company, June 1998, p. 13). Even when a U.S. carrier is not directly involved in an accident, NTSB frequently has an interest in its outcome because such accidents can have implications for operators of similar aircraft. As a consequence, the future demand for NTSB's accident investigation services will be significantly affected by the success of worldwide--and not just domestic--efforts to reduce accident rates.

Figure 3.1 underscores the point that there is no clear future trend for accident rates. The NTSB must maintain a flexible long-term strategy for dealing with accidents, emphasizing its ability to leverage external resources to deal with the historic variability in accident numbers. It is apparent that the NTSB must strike a balance between bearing the expense of staffing for peak demand periods, and staffing for somewhat lower demand levels and accepting that a certain amount of overtime is inevitable.[4]

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[4]Such variability in accident occurrences also makes it more difficult to identify progress in accident reduction efforts with any certainty.

The Safety Research Agenda

Ongoing safety efforts have aimed for maximum effectiveness in reducing accident rates by focusing on the most common accident causes. As shown in Figure 3.2, the three most frequent causes of accident fatalities are controlled flight into terrain (CFIT), airmanship, and loss of control.[5] Note the disparity in CFIT fatalities for U.S. operators and operators worldwide. New ground proximity warning equipment, superior training, advanced air traffic control equipment, and improved operating procedures make CFIT a much less frequent occurrence for U.S. operators than for operators in the rest of the world.

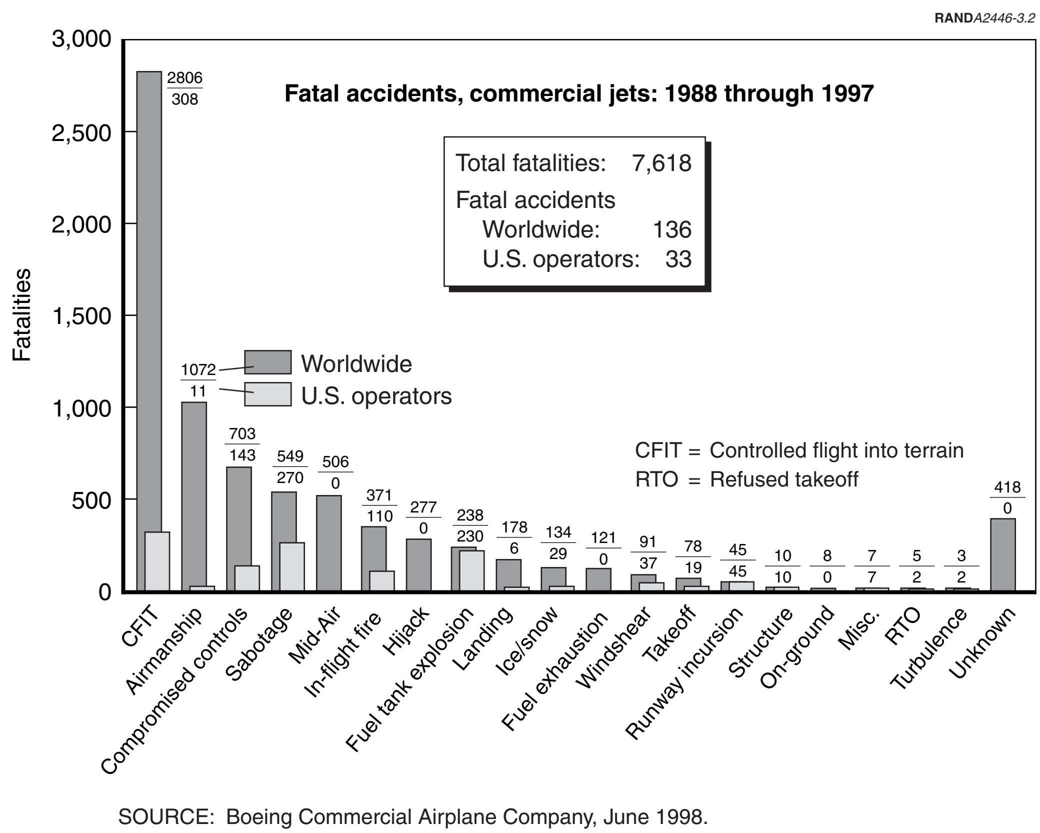

Figure 3.2--Fatalities and Fatal Accident Numbers by Cause of Crash

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[5]A CFIT event occurs when "a mechanically normally functioning airplane is inadvertently flown into the ground, water, or an obstacle." See Flight Safety Foundation, 1997, for a complete description of CFIT events and the steps being taken to prevent them.

Safety initiatives in the United States are already eliminating many of the most common causes of aircraft accidents. Consequently, the accidents that the NTSB may be called upon to investigate in the future could be much harder to diagnose. Investigating the crash of USAir Flight 427, which involved complex analysis of rudder design and pilot behavior, is one such example. Over time, the NTSB may see a reduction in the number of fatal accidents it investigates, but it may not experience a commensurate reduction in workload as accident investigations grow in complexity.

Accelerated Introduction of New Safety Technology

The greatest challenge in aviation today is being able to meet the need for increased capacity while simultaneously reducing the potential for an accident. Over the next 15 years, the NAS and the aircraft that fly within it will integrate technologies aimed at meeting this goal.

It will be critically important for the NTSB to keep abreast of these modernization initiatives as they are phased in. There may, in fact, be opportunities for the NTSB to shape the evolution of the system to better facilitate future accident investigations.[6] Many of the new technologies will introduce enhanced cockpit systems that increase the level of automation and dependence upon computer-based systems. Other changes will result from an extensive overhaul of the NAS architecture, including fundamental shifts in aircraft control, weather prediction, and communications.

Motivated by congestion, economics, and safety concerns, NAS modernization plans will touch on virtually every phase of aircraft operations, materially changing equipment, operational procedures, and the means by which NTSB captures information for diagnosing what happens in an accident.

[6]The implementation schedule for the National Airspace Architecture is divided into three phases: Phase 1 (1998–2002), Phase 2 (2003–2007), and Phase 3 (2008–2015). Phase 1 includes upgrades to controller computer workstations, deployment of satellite-based navigation systems, and air-to-air surveillance. Beyond Phase 1, the architecture is still evolving (Federal Aviation Administration, January 1999).

Most research into increased capacity focuses on three key areas:

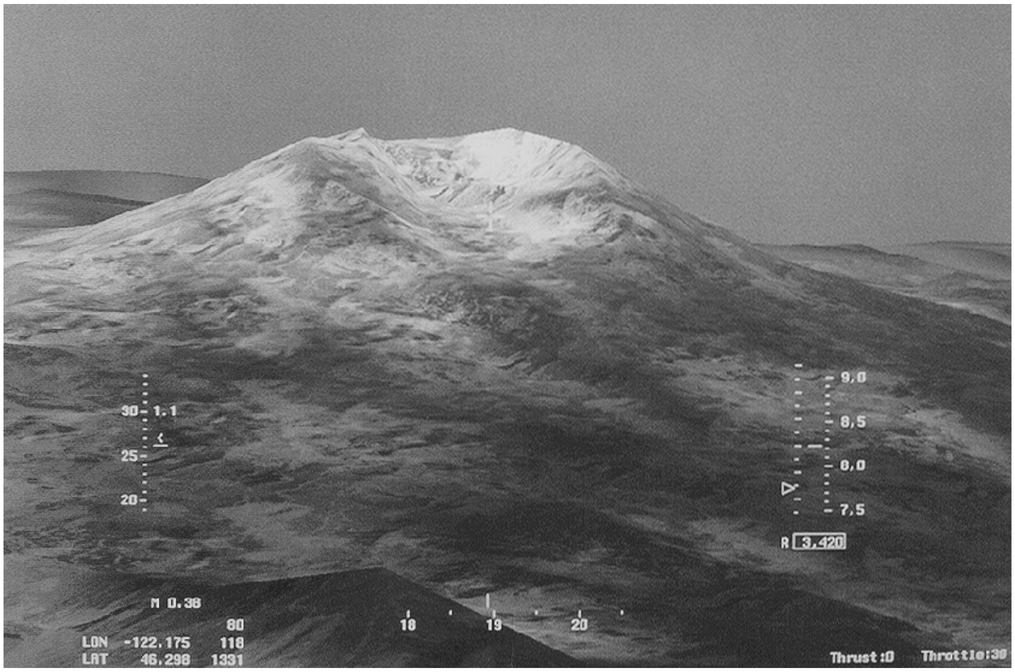
- improving the ability to fly in all weather and with higher densities of air traffic
- using airspace more efficiently
- processing aircraft through and around terminal areas more quickly.

Weather has long posed a threat to aviation safety. Perhaps the greatest threat stems from the pilot's reduced visibility. Many CFIT accidents are weather related. In the future, pilots will be able to use advanced technology to "see through the weather." This ability, combined with methods for predicting clear-air turbulence and other weather phenomena, will give operating crews and ground controllers a comprehensive map of what lies ahead.

Advanced weather monitoring systems integrate GPS systems for precision navigation with detailed computer-generated topographic maps, providing a view that is very similar to a flight view under visual meteorological conditions. This form of "synthetic vision," a sample of which is shown in Figure 3.3, is just one example of the emerging technologies aimed at reducing CFIT accidents.

Satellite-based precision navigation will also improve the ability of aircraft to accomplish all-weather landings. The FAA will approve Category I precision approaches using GPS-based technologies by 2001. Category II/III precision approaches will follow as augmentations to satellite-based navigation signals are deployed. The success of these improvements depends largely on the accuracy of weather forcasting information. However, the need for improved weather data has not yet adequately been addressed in the NAS architecture (Lindsey, December 31, 1998, p. 2-1). Improved accuracy and longer-range predictive models are essential to a more efficient NAS of the future.

The second of the key research areas listed earlier--more efficient utilization of airspace--relies on integrated communications, navigation, and surveillance (CNS) systems. Improved cockpit communications will advance the concept of a more self-reliant pilot, reducing air traffic controller workload and voice traffic congestion. Digital aircraft communication systems will increasingly rely on



SOURCE: Lewis, June 1998.

Figure 3.3--Synthetic Vision Display Prototype

satellite communications. Advanced CNS technologies will require a greater ability to account for all aircraft within a given location to ensure that flight path conflicts do not occur.

This advanced CNS is the foundation on which the concept of “free flight” is based. The FAA, NASA, and DOD are cooperating on the development of Automatic Dependent Surveillance systems with a broadcast capability (ADS-B). ADS-B systems will derive aircraft positions using GPS technology that locates aircraft with extreme precision. Aircraft identity, altitude, and position information will be integrated and digitally broadcast to ground receivers and the pilots of nearby aircraft. This precise location information will enable aircraft to operate at speeds and altitudes optimally suited to a flight.

Oceanic air travel is expected to grow by more than 30 percent over the next five years. To handle this expansion, the FAA is developing the Advanced Oceanic Automation System (AOAS), which aims to make oceanic flight more like free flight. To accomplish this, U.S. and overseas controllers, as well as en-route aircraft, must be able to share information and select flight profiles that accommodate higher traffic densities. With AOAS in place, pilots will be able to fly more fuel-efficient routes, taking advantage of aloft winds and using more efficient weather-avoidance procedures.

The third principal R&D initiative--improved airport and terminal operations--will create new cockpit and terminal displays that increase throughput and reduce delays.[7] Delays and congestion are often related to inclement weather. As air traffic increases, the ability to schedule arrivals and departures to achieve the smoothest possible traffic flow becomes increasingly important. The FAA and NASA are working together on improving air operations in the vicinity of airports. As a leading operator of aircraft in the nation, the DOD is drawing on its experience base of high-density air operations to contribute technical expertise to the effort.

NASA, under its Terminal Area Productivity program, is developing an array of advisory tools to permit higher densities of air traffic. For example, the Traffic Management Advisor (TMA) provides advanced graphical displays and alerts for air traffic controllers. The system generates statistics and reports about traffic flow and estimates the arrival time for each aircraft entering controlled airspace. TMA also recommends a runway assignment to optimize the traffic flow.

A Descent Advisor (DA) provides advisories that ensure fuel-efficient and conflict-free descents with arrival times accurate to within 10 to 20 seconds. NASA's Passive Final Approach Spacing Tool (P-FAST) is another decision support tool for air traffic controllers. P-FAST allows controllers to manage landing sequences and runway assignments to properly space the flow of traffic on final approach.

Other NASA initiatives aim to shorten the current separation requirements for landing aircraft in order to increase throughput. The Aircraft Vortex Spacing System provides precise separation measurements to prevent a landing aircraft from touching down before the wing-tip vortices from the preceding aircraft have safely dissipated. The system

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[7]The FAA reports that 23 of the nation's busiest airports are currently experiencing more than 20,000 hours of delays each year. Delays costs airline operators an estimated $3 billion annually and the congestion creates potential safety hazards (Federal Aviation Administration, June 1998).

uses sensors to measure the vortex and adjusts the separation requirements appropriately.

The Airborne Information for Lateral Spacing (AILS) system monitors the distance between aircraft approaching parallel runways using ground-based differential GPS devices. AILS will allow aircraft to safely operate in closer proximity as they approach parallel runways.

These efforts to land aircraft more efficiently will help to increase throughput. Nevertheless, simultaneous improvements in the flow of aircraft after landing are needed to prevent congestion on taxiways and ramp areas. NASA is pioneering a system called Taxi Navigation and Situational Awareness (T-NASA) which could significantly speed up aircraft movement to and from terminal gates. T-NASA will relay taxi instructions to the pilot’s computer and provide a moving image of the aircraft and other traffic in proximity to it. The system will allow pilots to safely taxi at higher speeds, even at night and during periods of low visibility.

A related system called Roll Out and Turn Off, which displays information to the pilot to optimize braking distance, will help to shorten an aircraft’s time on the runway. Ground controllers must also be able to monitor the location and movement of aircraft moving to and from gates. The FAA and NASA are jointly developing a Surface Movement Advisor, which integrates airline schedules, gate information, flight plans, radar data, and runway configurations to help ground controllers better control the movements of arriving and departing aircraft.

Other new systems are designed to prevent conflicts in low-visibility conditions. An example of this technology is NASA’s Dynamic Runway Occupancy Measurement (DROM) system. By predicting the time it will take for a given type of aircraft to land and clear a runway and then passing this information to other flight planning systems, DROM determines the spacing of landing aircraft, which ensures that runways are clear of conflicting traffic.

This proliferation of advanced technology designed to meet the pressing demands of increased safety and performance may also introduce new safety threats into the commercial aviation equation. Increased reliance on satellite-based navigation, for example, carries with it some measure of risk. The most significant threat to safety--intentional jamming of GPS signals during critical phases of flight--poses a significant hazard (Corrigan et al., 1999, p. 5–6; Federal Aviation Administration, October 1998, p. 18).

Systems that migrate into the cockpit will likely increase pilot workload. With the emergence of new computer-screen “glass-cockpits,” complaints from pilots regarding work levels are on the rise. These workload problems are heightened when ground controllers make last-minute changes to flight profiles or fail to fully appreciate the performance characteristics of new aircraft.

A recent study conducted by the Australian Bureau of Air Safety Investigation (BASI) found that nearly 60 percent of surveyed pilots think that ground controllers do not fully understand the capabilities of the aircraft the pilots operate (Bureau of Air Safety Investigation, June 1998, p. 22). More than 60 percent of the pilots surveyed reported that automated systems generated actions they did not anticipate (Bureau of Air Safety Investigation, 1998, p. 32). Nevertheless, pilots appear ready and eager to accept and work with the new technology. Only 10 percent of pilots thought that too much automation had crept into the cockpit and 70 percent expressed confidence that crew management aboard advanced technology aircraft posed no problem (Bureau of Air Safety Investigation, June 1998, pp. 30, 35). These results correlate with similar studies conducted in the United States (Federal Aviation Administration, June 1996; Wiener, June 1989).

The systems described here are directed toward transport category aircraft; fewer efforts are underway to integrate GA aircraft with new operating concepts. The large numbers of small aircraft operating in the new NAS will require affordable avionics. GA operators have little or no ability to recoup the cost of new equipment. Therefore, integration of advanced technology into the GA fleet tends to happen slowly and the impact of R&D initiatives for increased safety will be less immediate in the GA fleet.

Federal R&D programs are attempting to bridge the gap between transport and GA aircraft technology through joint initiatives with the avionics industry. For example, developing low-cost avionics is an objective of NASA’s Advanced General Aviation Transport Experiments program, but commercial availability is several years away. Furthermore, funding cuts for aeronautics research have limited the program’s scope (Warwick, May 1998, p. 6). Ensuring that air transport and GA aircraft can safely operate together in the new NAS will require careful planning.

In addition to becoming familiar with how a new system operates, NTSB investigators will need to learn where information resides in the system and how to extract it after an accident or incident. For instance, datalink messages may eventually replace voice communication records, and GPS-based position reports from individual airplanes may eventually replace centralized radar tracking records. While the new NAS could ultimately provide a richer collection of information to be used for accident diagnosis, its operation will require an enhanced skill set. The NTSB will encounter significant training challenges over the next two decades as the system evolves and is deployed.

GROWING COMPLEXITY IN AVIATION: IMPLICATIONS FOR THE NTSB

To overcome limitations in performance or reliability, most “inventors” deliver solutions that merely build additional complexities onto existing structures. Every once in a while an inventor comes along who does just the opposite, and solves a problem by making a complex system simple. A good example is Frank Whittle and his invention of the turbojet engine. It came at a time when aircraft piston engines had become layered with complex systems such as turbo-superchargers and power recovery turbines designed to extract every ounce of available horsepower. As might be expected, the jet engine of today is itself a study in complexity that bears only a vestigial resemblance to Whittle’s original.

Increasing complexity is a natural phenomenon and one familiar to the NTSB. Nevertheless, the implications of growing complexity in aviation will likely have a profound impact on future NTSB operations. Future aircraft will be far more reliable, but the challenges associated with tracing the circumstances of their failures will require new ways of doing business. The following sections examine some of the factors the NTSB must examine as it enters the age of extraordinarily complex systems.

Increasing Reliability of Aircraft and Ground Systems

Dramatic improvements in flight safety are largely made possible by increasingly reliable aircraft. Improvements in the reliability of aircraft systems can be traced to four primary sources:

- **High Reliability (Hi-Rel) parts and components.** The performance of both mechanical and electrical devices continues to improve. Electronic parts improvements have been especially dramatic. As Figure 3.4 shows, high-grade commercial electronic parts (unscreened parts) are now as reliable as military-grade equipment (Class B and Class S screened parts). NASA and Air Force Hi-Rel R&D programs are significantly improving component performance in aerospace applications.[8]
- **Improved test techniques.** Underlying the drive for improved quality and reliability is a shift from empirical explanations for failure mechanisms to a more scientific approach. The *physics-of-failure* method, for example, applies reliability models, built from exhaustive failure analysis and analytical modeling, to environments in which empirical models have long been the rule.
- **New system design approaches**. Improved design techniques are being employed to reduce the risk of errors. Integrated product teams (IPTs) are credited with facilitating communication among design teams, thereby reducing preproduction problems. Better control of technical requirements has helped streamline the development process and further reduce errors. In addition, collaborative techniques such as the Computer-Aided Three-Dimensional Interactive Approach (CATIA) and simulation-based design enable engineers to catch design errors early in the development cycle.

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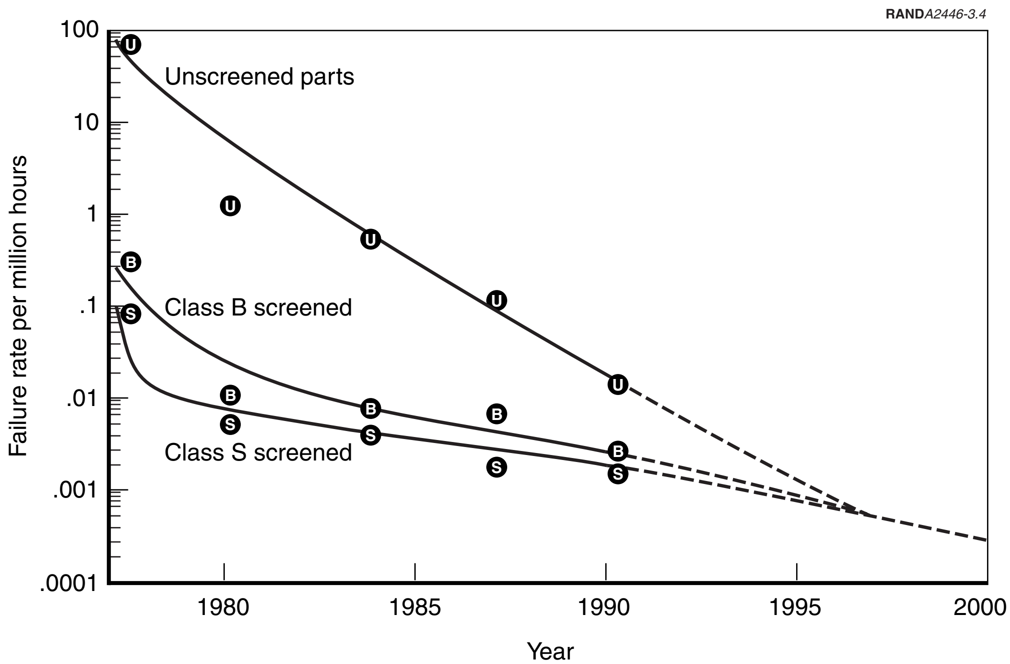
[8]The Air Force Reliability Analysis Center at Rome Air Force Base monitors Air Force initiatives related to high reliability. At NASA, programs are coordinated out of the Office of Safety and Mission Assurance in Washington, D.C.



SOURCE: Plum, 1990.

NOTE: Class B and Class S parts refer to military-grade components; Class S parts are rated for spaceflight.

Figure 3.4--Decline of Electronic Parts Failure Rates

- **Increased emphasis on product assurance.** In the past, individuals charged with the product assurance function served primarily as "assurance police." Today, product assurance is more often integrated into the design effort, providing up-front quality management.

Advancements in the performance and reliability of aircraft systems should lead to steady improvements in safety. However, increasing complexity will continue to challenge the ability of engineers to eliminate design errors before new aircraft and systems are fielded.

Design-Related Accidents: A Growing Danger

The first fatal crash of a powered aircraft was traced to a design-related failure (Crouch, June 1990). As aviation science yielded increasingly sophisticated design tools, other failure modes became the dominant cause of aircraft accidents. Paradoxically, although the overall aviation system will likely experience continuous improvements in safety, and therefore lower accident rates, a greater percentage of incidents and accidents in the future will likely be traced to design problems. This is primarily because design-related events are not likely to decrease as quickly as events related to other causes of accidents and incidents.

The causes of failure can be sorted into five categories: environmental factors, failure of systems and electronic parts, quality defects, operator error, and design-related problems.[9] (A generic "unknown" category is also used for cases in which cause cannot be established.) Table 3.1 presents a qualitative assessment showing that design-related problems are likely to rise proportionately to the following trends:

- **Crashes caused by environmental factors are decreasing.** A great deal of research has focused on reducing the number of accidents caused by environmental factors. Wind shear accidents, for example, have been largely eliminated in recent years. CFIT accidents are also on the decline. Like other accidents that trigger safety improvements, the 1974 CFIT loss of an airliner approaching Washington's Dulles airport prompted the FAA to mandate the use of Ground Proximity Warning Systems (GPWS). In the United States, the accident rate for domestic airline accidents attributed to CFIT dropped from an average of eight aircraft per year to one aircraft every five years following the implementation of the new GPWS technology (Bateman, November 1994, p. 2). As in the case of wind shear accidents, the drop in the rate of accidents attributable to CFIT can be traced to many factors: new on-board and air traffic control systems (such as GPWS and the implementation of Minimum Safe Altitude Warning Systems in tower radar), improved training programs, and educational programs for pilots and controllers.[10]
- **Relatively few accidents are caused by on-board system failures.** Current data from Boeing indicate that only about 10 percent of

[9]This categorization is taken from military and civil databases used to track failures in aerospace systems.

[10]While the rate of CFIT accidents and incidents has been substantially reduced, further reductions in the rate have proven difficult to achieve (Menzel, April 1998).

accidents are caused by aircraft systems failures (Boeing Commercial Airplane Company, June 1998, p. 21). A 1971 analysis of aircraft avionics failures traced 50 percent of system failures to problems with parts. Less than 20 years later, a similar study conducted in 1990 found parts failures to be negligible (Pecht et al., December 1992, p. 1161). System reliability improvements will continue to significantly reduce these types of failures.

- **Operator error is often rooted in design problems.** Pilot error constitutes by far the largest proportion of the accident and incident cause record, cited in an estimated 55 to 75 percent of accidents and incidents. However, the tendency to cite "operator error" is being reexamined, as it can mask more complex interrelated causes (Greenfield, November 1998a, p. 15). Experts are beginning to suspect that the human-machine interface is the true source of many operator errors. For instance, pilot uncertainty over computer modes in the cockpit continues to be a potential source of safety problems (Phillips, January 30, 1995, p. 63). Future investigations are likely to implicate design problems as either the probable or contributing cause of accidents that would have previously been attributed to pilot error.

Advanced design tools, new methods of organizing design teams, and increased collaboration among designers have helped manufacturers improve the performance and reliability of aerospace systems. Research has also been conducted to validate design algorithms. For example, studies have attempted to correlate accident and incident statistics with design parameters, such as lift and stability characteristics or power and wing loading. Generally, this research has concluded that the design practices in use today produce robust safety margins.[11]

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[11]One study has suggested that a correlation exists between directional stability and accident tendencies in commuter aircraft (Smith and Gerhardt, August 11, 1993). Also, some alarming incident and accident trends are prompting a careful consideration of some design selections. The decision to forgo leading edge slats on some regional

Table 3.1

Projected Changes in the Cause of Failures

Failure factors	Failure trend	Technical forces driving trend	Percentage of cause
Environment	↓	• T/ADWR, LIDAR systems • GOES-Next, space-based surveillance upgrades • Synthetic vision and "through the weather" HUDs • Improved ice detection/removal systems	↓
Design	↓	• Integrated product design, product design centers • CAE, CATIA • Simulation-based design	⇧
Parts	↓	• Hi-Rel parts and components • "Pick and Place" machines, surface mount manufacturing • MEMs, MCMs, Ultra-PEMs • CARMA	↓
Quality	↓	• Physics-of-failure strategies • Improved testing/screening techniques • Embedded PA	↓
Operational	↓	• Improved flight/maintenance/operations simulation • TCAS II, EGPWS, IDACS, next generation CNS • GPS precision nav, ADS-B, AOAS • Reclassification of human factors–type accidents	↓
Unknown	↓	• Fault tolerance/isolation systems • Improved failsafe and error detection techniques • Increase in FDR parameters	—

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Although engineering practices continue to improve aircraft design and introduce increasing levels of safety, they will likely be outpaced by the reduction of failures from environmental factors or problems with on-board systems. The greater scrutiny being paid to operator-related events is also likely to reduce operator error as a primary source of failure. The net result of these trends is that a growing proportion of aviation accidents will be traced to design-related failures.[12]

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jet aircraft, for example, has led to concern over the operation of aircraft without leading edge slats in icing conditions.

[12]Previous RAND research noted a similar trend of a growing proportion of design-related failures in the satellite industry (Sarsfield, 1998, p. 119).

A rise in the proportion of design-related events will require the NTSB to make changes in the way it conducts accident and incident investigations:

- First, because design failures can have fleetwide implications, parties to an accident are likely to be more guarded during investigations. The Safety Board should anticipate having to expend more resources in such circumstances.
- Second, design-related failures are likely to involve more testing, research, analysis, and simulation to uncover hidden failure modes.

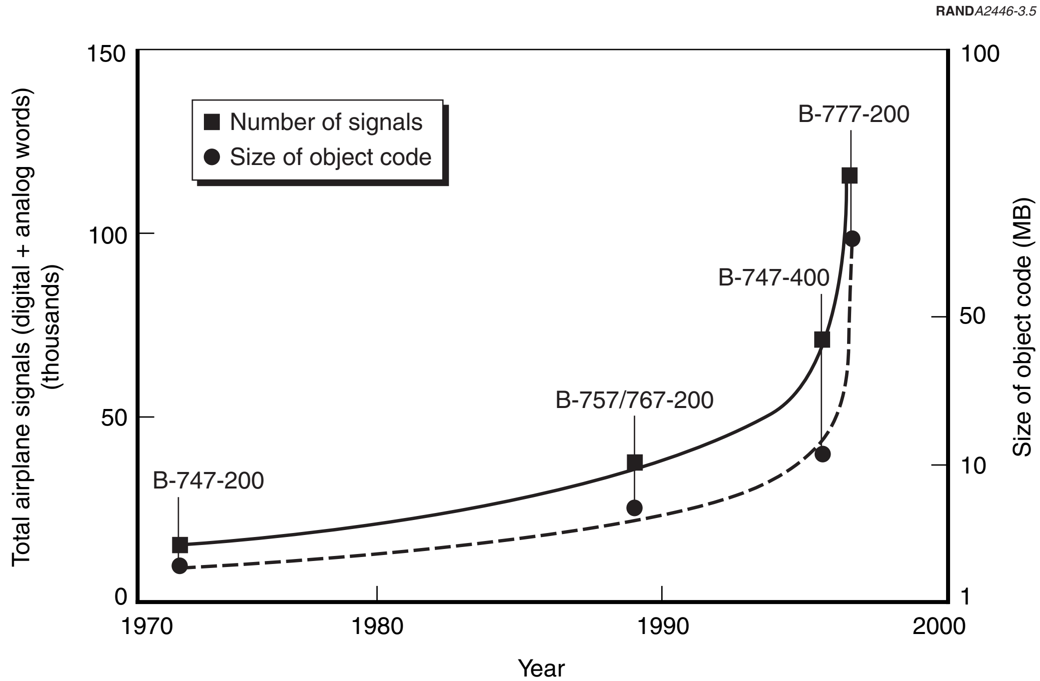
For both these reasons, the NTSB will need to improve its relationships with external organizations and rely more heavily on outside expertise.

In summary, while declining accident rates may imply a decrease in the NTSB's workload, it is more likely its workload will actually increase. When dealing with design failures, the NTSB's investigations will demand a greater amount of research and a shift in staff skills and experience (see Chapter 5 for further discussion). The Safety Board will need to develop new alliances to tap a knowledge base it cannot afford to maintain on its own.

Additionally, the NTSB will need better analytical tools, along with new ways to simulate the performance of designs in action. Design errors can be found in any system, but because glitches are often due to a failure to anticipate certain interactions among the system components, or between the system and its environment, they will occur more frequently as the number and complexity of system behaviors and interaction grows. This is the subject of the next section of this chapter.

NTSB Will Need New Investigative Methods

The increasingly complex electrical and mechanical systems that operate aircraft have long challenged accident investigators. Figure 3.5 illustrates two examples of growing complexity--the increase in signal architecture (digital and analog) and installed software (megabytes of code) in Boeing aircraft. Here the growth is exponential. These trends,



SOURCE: Weener, 1997.

Figure 3.5--Increasing Complexity in On-Board Software

however, tell only part of the story. The growing complexity of individual systems is compounded by the increasing interconnectedness of systems. In the past, aircraft operated with single-point, sensor-to-instrument systems. Current-generation aircraft, by comparison, operate with highly integrated systems with extensive cross-linking.

Complex systems are often highly interactive and tightly coupled; failures in one area can propagate rapidly to other areas. Some analysts have concluded that accidents involving complex systems are inevitable and have coined the term "normal accidents" to describe them.[13] In aviation, however, accidents do not appear to be "normal." Engineers understand a great deal about the operation of complex systems and have reduced coupling by using robust designs that contain built-in fault isolation and redundancy. These design improvements allow modern aircraft to operate with both unprecedented complexity *and* reliability.

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[13]The earliest use of this term was by Charles Perrow in his seminal text *Normal Accidents* (Perrow, 1999).

It is interesting to note that many cases of failures in complex systems can be traced to the failure of safety systems themselves (Langewiesche, March 1998, p. 98).

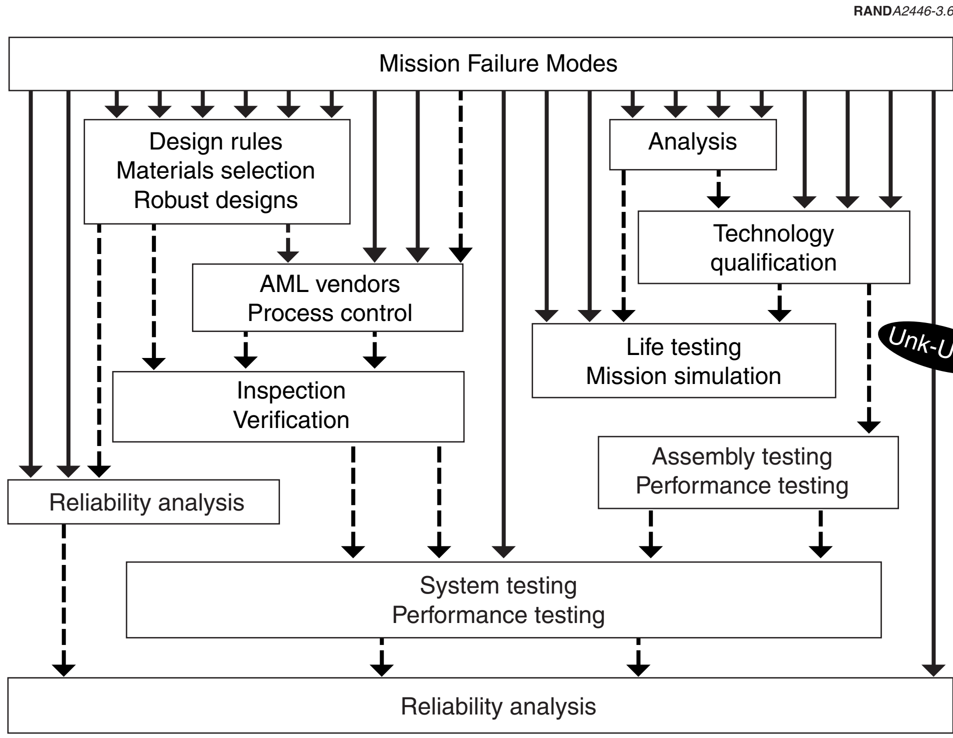
Although systems are becoming safer, their growing complexity raises concerns that should be addressed by the NTSB. The potential for problems is especially acute in relation to human-machine interactions, as noted by a former NTSB manager:

> I doubt that any manufacturers' aircraft are completely free of potential for human error incidents and/or accidents; i.e., they have in their design, . . . pathogenic bugs that will only become manifest under the "right" set of conditions, sometimes with only embarrassing consequences, and sometimes with tragic ones (Lauber, September 19, 1994).

Most notably, manufacturers may be less able to predict the many failure modes inherent in a complex design. Figure 3.6 is a high-level depiction of the stepwise methods used to eliminate defects and potential failure modes from engineering designs. The right side of the figure includes a mode for so-called unknown-unknowns ("unk-unks") that engineers have not considered and that existing tests are unable to eliminate.

Extensive research continues on new quantitative methods for identifying design defects or production errors, but a gap still exists in the ability to assess the expected reliability of highly complex systems. This is especially true in the area of computer software. Increasingly, aircraft functions rely upon software. Aircraft manufacturers are faced with the task of improving performance and reliability while remaining cost competitive. Higher levels of integration, largely enabled by a growing reliance on software, allow engineers to accomplish these tasks.

Electronic systems are also replacing many mechanical components. This is most notable in flight control systems (fly-by-wire) but also in other areas such as digital fuel control units and fully electronic navigation systems. Higher levels of integration and greater use of electronic components demand increased software requirements. Software is, by its nature, a malleable product that is likely to receive



SOURCE: Cornford, 1996, p. 4.

NOTES: 1) Each box represents a collection of Preventions, Analyses, Controls, and Tests (PACTs).
2) Dotted lines represent "escapes"—undetected/unprevented failure modes.

Figure 3.6--Defect Propagation Model

extensive modification, expansion, and re-engineering prior to integration into a larger system. It is reasonable to expect, therefore, that errors and faults in overall systems increasingly will be traced to software.

Detecting faults in software is notoriously difficult. The implications of even minor code errors were graphically demonstrated by the loss of an Ariane 5 launch vehicle on June 4, 1996. The investigation revealed the cause of the accident to be a design error in the vehicle's inertial reference system software (European Space Agency, July 19, 1996). More recently, the Air Force lost a Milstar spacecraft because of an inaccurate software load that apparently went undetected during the validation process (Covault, May 10, 1999, p. 28).

Typically, software engineers must rely on testing, diversity in design, and fault tolerance to remove errors or reduce their impact. For ultra-reliable, safety-critical applications, testing using statistical risk quantification or classical methods is not feasible because an extraordinarily long test time is needed to achieve high levels of assurance (Butler et al., January 1993, p. 7). The use of parallel design teams to develop independent software solutions for a given set of requirements has also been shown to be unreliable (Holloway, October 1997, p. 9).

That leaves techniques that seek to avoid faults as the most appropriate for safety-critical applications. Of these, so-called "formal methods"--the application of discrete mathematical proofing tools—have been found to be highly effective in safety-critical applications, such as aircraft flight control systems (National Aeronautics and Space Administration, July 1995b, p. 30). Formal methods employed during the specification and verification phases of software development help to reduce faults in software elements, but they cannot eliminate doubts about the overall performance of a system (Rushby, May 1993, p. 139). Formal methods can, however, help engineers understand the overall fault environment and create more fault-tolerant designs as a result.

Although the NTSB has long dealt with rising complexity, two factors will drive a fundamental re-ordering of investigative management and processes. The first is the large number of potential failure scenarios that need to be evaluated in a complex systems accident. The second is the impermanent nature of evidence associated with a complex systems event.

Only a limited number of crashes, even among the latest generation of aircraft, will likely be caused by a systems-related failure. When such events do occur, however, NTSB investigators should expect to rigorously explore a significant number of failure potentialities. During the investigation of a complex systems accident, the NTSB will probably face the following challenges:

- **Lack of failure mode data.** The manufacturer may not be able to provide ready information after an accident because the failure mode may not have been experienced before. In cases such as this, parties to the accident will be less able to respond quickly to information requests from the NTSB.

- **Exhaustion of resources.** Complex events multiply the number of potential failure scenarios. Limited NTSB resources could cause investigators to perform failure analyses serially instead of in parallel, greatly prolonging the analytical phase of the investigation.
- **Demands for specific expertise.** The ability to examine failure scenarios will require diverse yet highly focused technical skills that often are beyond the range of Safety Board personnel. Individuals managing the investigation will need to identify outside experts and enlist their support quickly, often outside of traditional party mechanisms.

NTSB investigators have already witnessed the extraordinary number of failure scenarios the crash of a modern aircraft can generate. In the USAir Flight 427 investigation, for example, the accident team dealt with a virtually endless number of possible scenarios (Harr, August 1996, p. 49). Such accidents will require the NTSB to develop new methods for running simultaneous analyses, prioritizing resources, and assessing the probability that any given scenario may be the right one.

The fact that complex events may fail to present clear reasons for equipment or system failures poses a considerable challenge to traditional Safety Board investigative practices. RAND found that NTSB investigators are well prepared for accidents in which the failure mode reveals itself through a careful examination of the wreckage. An appreciation for the fact that catastrophic failures can occur in complex systems without obvious physical evidence was less apparent. The "broken bolt" or "severed cable" represents the type of mechanical failure that can be located quickly by analyzing debris. This type of "permanent state" failure is readily identifiable. In complex systems, "reactive state" failures can occur (Gerdsmeier et al., June 1997, p. 1; Ladkin, June 1998). Such modes of failure do not persist and therefore evidence needed to trace the cause of failure is not available to investigators.

As complexity increases so does the need for enhanced observation of systems performance during a failure event. The ability to "observe" the performance of an aircraft is determined by the fidelity of the FDR.

New aircraft carry high-fidelity FDRs, and this will likely improve the ability of the NTSB to establish what happened during an accident. However, additional analysis will be necessary to determine whether high-fidelity FDRs will more quickly reveal the cause of failures in complex systems.

Increasingly complex systems underscore the importance of ongoing training. Operators of complex systems must reach a performance level that matches the capabilities of the system (Flight Safety Foundation, December 1994, p. 10). In a similar vein, accident investigators must be trained not just in investigative techniques but in a broad, multidisciplinary routine that reflects the complexity of the systems they will be called upon to analyze.

This type of long-term training program cannot be fully implemented with internal NTSB resources alone. The NTSB will need to develop cooperative relationships with aviation industry manufacturers and operators, university-based researchers, and other government agencies.

THE CHANGING COMPOSITION OF THE TRANSPORT FLEET

Air travel continues to increase in popularity. Significant growth is projected in both the number of passenger miles flown, domestically and overseas, and in the size of the fleet needed to meet the increasing demand. The NTSB must plan for a larger and more diverse fleet and for changes in the manufacturing base of suppliers.

The FAA projects that between 1997 and 2010, domestic flight hours will increase by 56 percent for air carriers, 81 percent for regional/commuter carriers, and 25 percent for general aviation (Federal Aviation Administration, June 1998). This is in line with forecasts of worldwide commercial air travel growing by roughly 5 percent per year for the next 10 years in the air carrier segment (Boeing Commercial Airplane Company, June 1998).

This growth in the air carrier segment is expected to double the number of aircraft in the worldwide air carrier fleet by 2015, as shown in Figure 3.7. The air carrier growth is accompanied by several parallel trends: aircraft types and systems will proliferate, the number of foreign-built aircraft will increase, aircraft will carry more passengers, and the overall aircraft fleet could be older. These trends, which are discussed in the following sections, must be addressed by NTSB senior managers who are charged with keeping pace with change.

Diversity of Aircraft Types and Systems

Figure 3.7 shows that manufacturers see only a limited market for completely new aircraft designs. Airlines will purchase additional or replacement aircraft that are for the most part evolved from current designs. The fact that radically new aircraft designs (such as the supersonic transport) are not in the offing somewhat lessens the NTSB's responsibilities in regard to training or hiring.

Nevertheless, even serial improvements in current designs will present a challenge to aviation accident investigators. Significant design changes accompany each new aircraft series, particularly in the aircraft's onboard systems. Cumulatively, these system changes can produce designs that bear only a structural resemblance to the original aircraft. Additionally, operator-selected options and modifications

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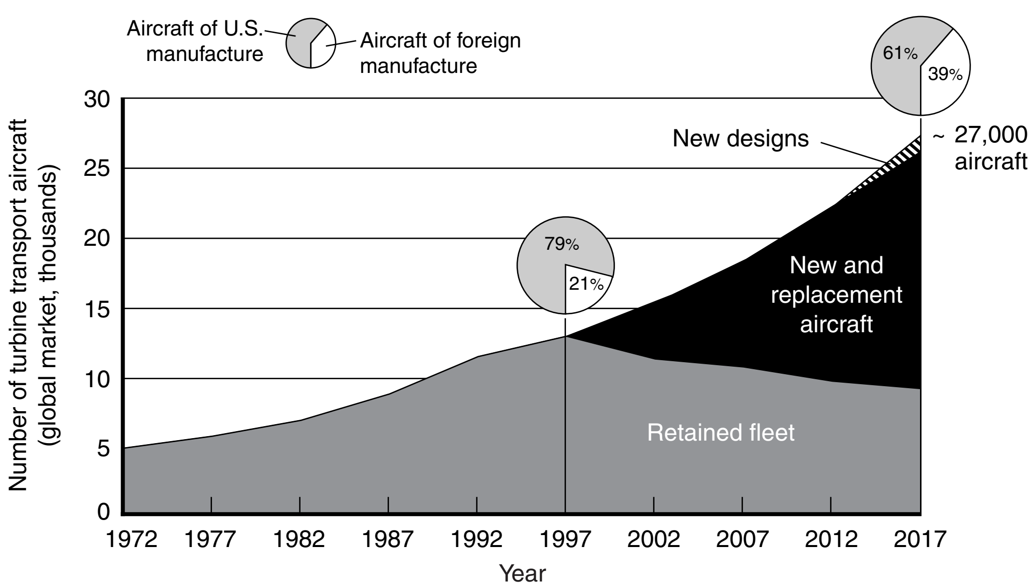

SOURCES: Boeing Commercial Airplane Company, June 1997; Airbus Industrie, April 1998.

Figure 3.7--Projected Future World Transport Fleet

produce tremendous diversity among aircraft within a fleet. After an accident, NTSB investigators will need to consult closely with both the manufacturer and the aircraft operator to fully understand how the aircraft is equipped and how it might have performed during an accident.

This diversity within a fleet poses a systems-level challenge to the NTSB. Training programs should be designed to focus on the most generic components of change. Identifying features that are common among aircraft whenever possible will allow the NTSB to better target its training programs.[14] In addition, instruction on new technologies that underlie the development of new systems, such as GPS-based navigation techniques, should form a core element of any training program.

As the world transport fleet doubles in size over the next two decades, the percentage of aircraft built by non-U.S. manufacturers is also expected to nearly double, from 21 percent to 39 percent. During 1998, the number of Airbus Industrie orders came to within 100 of Boeing's aircraft orders, although deliveries by Airbus lagged by several hundred airplanes.[15] Airbus Industrie's goal is to acquire a sustainable 50 percent share of the aviation market (Sparaco, October 5, 1998a, p. 5).

As U.S. and foreign carriers increase their use of foreign aircraft, NTSB investigators will have to become much more familiar with their design and operation. They must also be prepared to work with the foreign aviation community, including manufacturers, operators, regulators, and accident investigators.[16]

Larger Aircraft with Higher Passenger Densities

In the worst crash in aviation history, two Boeing 747s collided in 1977 in Tenerife, Canary Islands, killing 578 passengers and crew. As

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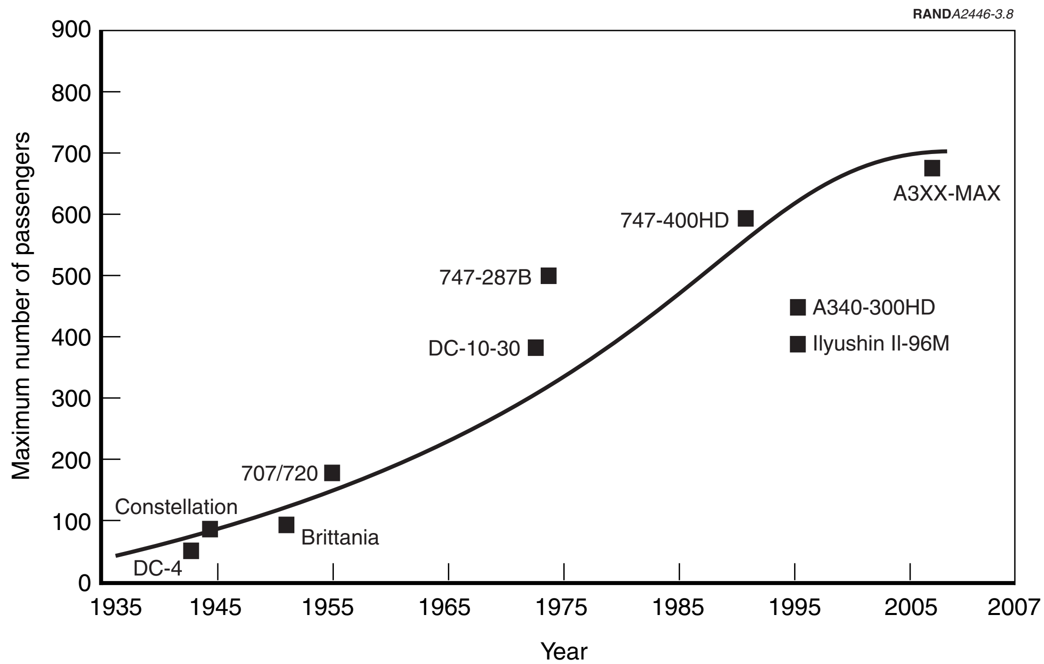
[14]Cockpit procedures for the Boeing 757 and 767 are similar, for example. The Airbus series of transport aircraft have extensive cockpit commonality.

[15]Sales figures were developed directly from data available from the Boeing Commercial Airplane Company (www.boeing.com) and Airbus Industrie (www.airbus.com) Web sites.

[16]This is equally applicable to the regional/commuter aviation segment, in which the vast majority of the U.S. fleet is from foreign manufacturers.



SOURCE: *Jane's All the World Aircraft*, multiple years.

Figure 3.8--Growth in Passenger Capacity of Transport Aircraft

shown in Figure 3.8, aircraft passenger capacity has grown to the point that an event of the magnitude of the 1977 crash could involve just a single aircraft. Alarmingly, incidents have occurred that clearly demonstrate the potential for just such a disaster.[17]

Industry planners are now considering building very large transport airplanes capable of carrying up to 800 passengers. Such designs will strain safe aircraft operations. For example, although emergency evacuation of several hundred passengers (which currently must be done in under 90 seconds) has been demonstrated in certification tests, it is thought by many to be impossible during an actual emergency.

As aircraft design measurably improves, so does the public's expectation that even higher levels of safety will be achieved. A single

[17]In 1998, a United Airlines Boeing 747 with 307 people aboard narrowly missed a hill after experiencing an engine loss on takeoff from San Francisco International Airport (Carley, March 19, 1999). This, and similar close calls, could be harbingers of a domestic accident of unprecedented proportions.

event in which close to a thousand people are killed would certainly receive unprecedented media attention. An accident of such magnitude would also severely tax NTSB resources, leaving limited resources for other investigations. Furthermore, aircraft such as the Boeing 747-400 combine unprecedented passenger capacity with the latest-generation technology. Should a major fatal accident occur, and should it involve complex design-related issues, the event could consume virtually the entire Safety Board aviation staff.

Accidents resulting in a large number of fatalities focus increased public attention on the NTSB and its operations, creating a very challenging work environment. The average passenger capacity of commercial transport aircraft is projected to increase over the next two decades, although this could be tempered by the airlines' tendency to add capacity by increasing the number of flights rather than by flying bigger planes.[18]

Increasing the passenger capacity of regional/commuter aircraft that operate at high flight frequencies offers comparatively greater leverage in terms of reducing airport congestion. For this reason, the FAA projects a marked increase in the size of aircraft in future U.S. regional/commuter fleets.[19]

The Aging Fleet

In the past, airlines operated aircraft as long as possible, with the assurance from manufacturers that safe operation could be maintained provided inspections and maintenance were routinely performed. Boeing estimates that approximately 20 percent of all commercial jet airplanes flying today are considered to be "aging" airplanes (McGuire, April 1998, p. 4), meaning that they have exceeded their original design

[18]During the next 10 years, Boeing projects larger aircraft will account for an 8 percent growth in available seat miles, longer routes will account for a 3 percent growth, and increased flight frequencies for 89 percent of the growth. The 8 percent growth, while seemingly modest, still represents five times as much growth in available seat miles due to larger airplanes than occurred in the prior 10 years (Boeing Commercial Airplane Company, May 1998, p. 35).

[19]Between 1997 and 2009, the FAA projects the proportion of U.S. regional/commuter passenger aircraft having 20 or more seats to grow from 50 percent to 71 percent (Federal Aviation Administration, 1998a).

service objective (DSO). The DSO of U.S.-designed commercial airliners is 20 years.[20] Most of the first- and second-generation jet aircraft in the commercial fleet have exceeded this limit. The average Boeing 737-100, for example, is 29 years old, and GA fleet aircraft are estimated to be 28 years old on average (General Aviation Manufacturers Association, 1998, p. 11).

A reverse trend is emerging in the commercial aviation fleet. In the modern air travel marketplace, the need to maintain an up-to-date image, conform with noise abatement requirements, and hold down maintenance costs is making operators rethink their strategies on retiring aircraft.

As shown in Figure 3.9, airlines today do not expect to operate an aircraft for more than 30 years. Therefore, it is reasonable to assume that potential issues associated with the safe operation of aging aircraft will decline in the long-term because of the lower percentage of aging aircraft. However, the NTSB could face aging issues in the near term. Because aircraft retired from domestic service often enter service with foreign carriers, and because the NTSB increasingly is called upon to assist with international investigations, the NTSB's workload could increase if problems with aging foreign-owned aircraft develop. Whether or not age affects the safe operation of aircraft is clearly an issue that could influence NTSB planning.

It is unfortunate that research in regard to aging aircraft systems has lagged behind the airline industry's decisionmaking. Although the FAA and DOD are finalizing analytical methods that will quantify the risks related to operating aircraft beyond their design lives, some airlines have nevertheless elected to depend heavily on older aircraft.

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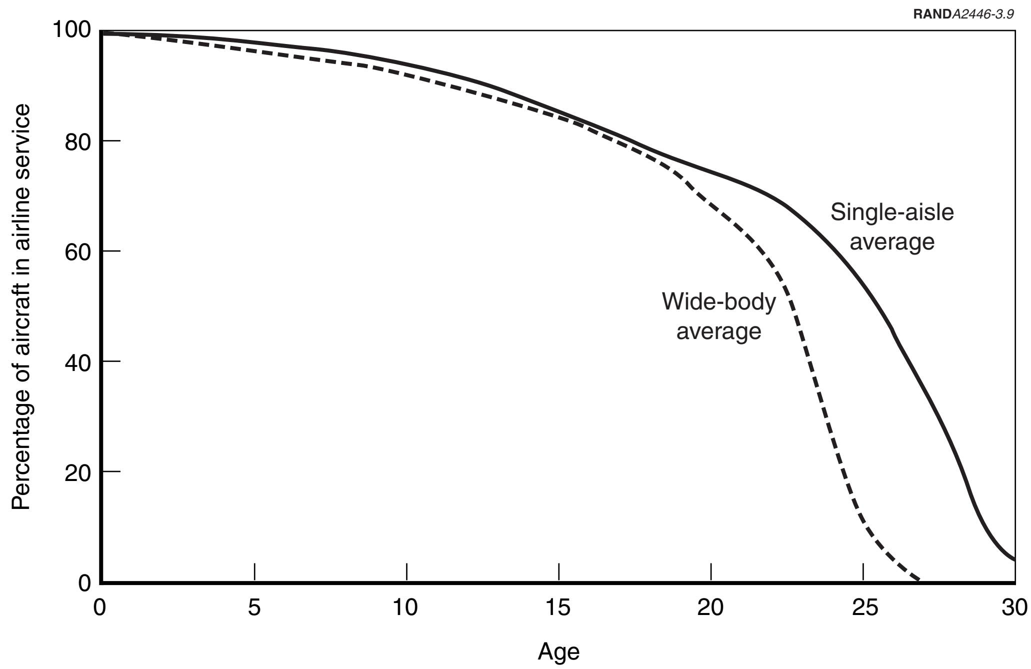
[20]It is important to remember that the DSO of an aircraft is a goal related only to an aircraft's primary structure, not to systems placed within the structure. The DSO essentially seeks to ensure that the airframe remains free of significant fatigue cracks during a 20-year period given expected utilization rates.



SOURCE: Airbus Industrie, *Global Market Forecast*, 1999.

Figure 3.9--Operator Strategies for Aging Aircraft

In the past, some carriers saw a cost advantage associated with forgoing the purchase of new aircraft and opting instead for renewal of older ones. In 1994, for example, Northwest Airlines chose to expand its fleet of older DC-9 aircraft and refurbish them to meet current standards. Although the decision saved the company the purchase price of new aircraft, substantial unplanned expenditures were required to ensure adequate maintenance. Published reports showed that the older fleet experienced unscheduled landings at a rate four times that of airlines operating similar but newer equipment, and that increased maintenance workloads required the airline to hire 1,200 additional mechanics (Carey and McCartney, June 12, 1998).

As an aircraft ages, growth in maintenance costs to keep the plane flight-worthy can be dramatic. How the aircraft is maintained, where it is operated, and how it is utilized throughout its life affect subsequent maintenance costs. Maintenance cost is also heavily influenced by the initial DSO and engineering choices made by the manufacturer.[21]

The Air Force's experience with aging aircraft indicates that aircraft can be safely operated well beyond the original DSO. Several Air Force systems are now more than 30 years old. The B-52 bomber and KC-135 tanker are the most notable cases, but the C-141 transport and T-37 and T-38 trainers are also aging platforms (U.S. Air Force, October 1998a, Table E-16). The Air Force currently operates 76 B-52Hs with an airframe limit of 32,500 to 37,500 hours on the upper wing surface (U.S. Air Force, March 1999, p. 21).[22] The Air Force plans to operate its B-52Hs until approximately 2040. At that point, the B-52H would be more than 80 years old.

A RAND study found that the Air Force fleet, currently averaging 20 years old but projected to climb to 30 years old over the next two decades, will probably incur rapid growth of maintenance costs along with the risk of loss of availability (Pyles, 1999). Similarly, a 1997 National Research Council (NRC) report highlighted the problems associated with maintaining an older military fleet (National Research Council, 1997). The NRC concluded that the economic burden resulting from aircraft maintenance could quickly become so overwhelming, and the availability of aircraft so uncertain, that the fleet could become nonviable. However, the *safety* of the Air Force's fleet may not be affected.

Figure 3.10 shows the Air Force's lifetime safety experience with its aging B-52 and C-135 aircraft, as measured by the rate of Class A mishaps.[23] The trends shown in Figure 3.10 are consistent with a general trend of declining Class A mishap rates for Air Force aircraft (U.S. Air Force, October 1998b). Although the Air Force may experience loss of availability of aircraft, reduced operating limits, and higher

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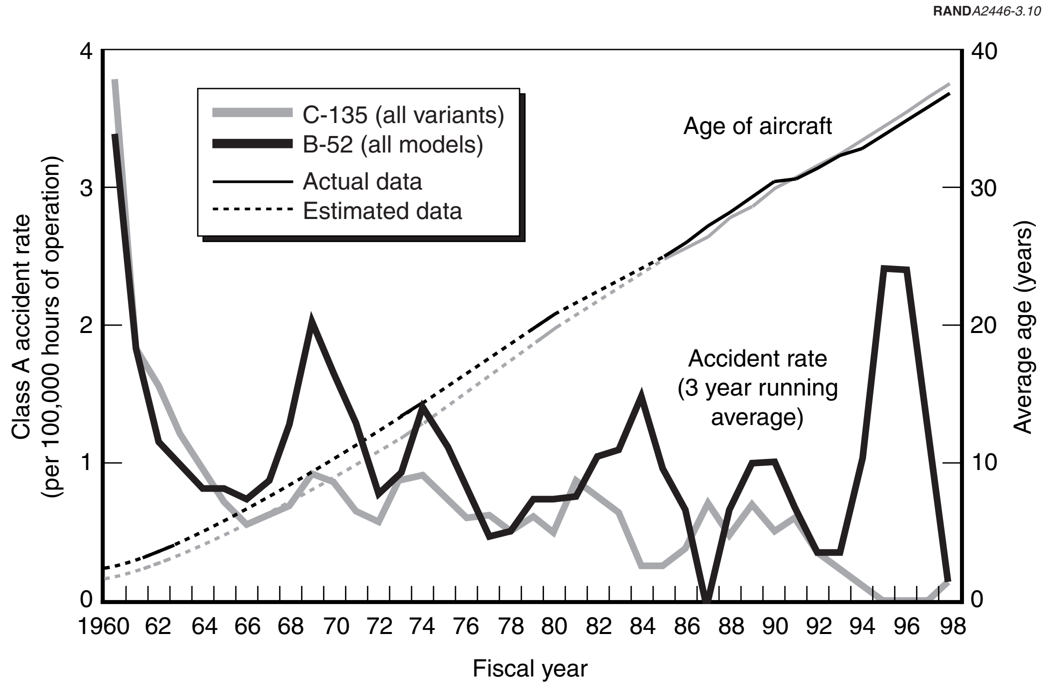
[21]A discussion of maintenance cost growth can be found in DiDonato, December 4, 1997.

[22]Earlier B-52 variants were retired from service. The H model continues to be modified to meet changing mission requirements.

[23]The definition of a Class A mishap has changed over time, but the term refers to a *severe* event, currently defined as damage in excess of $1 million, or an event that results in a fatality.



SOURCE: Compiled from the *U.S. Air Force Statistical Digest*, various years, and data provided by the Air Force Safety Center's Mishap Prevention and Epidemiology Branch (HQ AFSC/SEPR).

NOTE: Includes regular Air Force, Reserve, and Air National Guard active aircraft; excludes acts of war.

Figure 3.10--Accident Rates for C-135 and B-52 Models by Age of Aircraft

operational costs with its older aircraft, Figure 3.10 indicates no unusual loss rate associated with older systems.

Extrapolating military experience to the commercial aviation fleet is not, however, a straightforward affair. Large military aircraft typically fly far fewer in-service hours in a given year with far fewer takeoff-and-landing cycles than the typical commercial transport, and with less predictable patterns of use.[24]

Inspection and maintenance procedures on a military aircraft versus a commercial airliner are also quite different. The military's "inspect and repair as necessary" (IRAN) process is roughly equivalent to "D"

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[24]The average C-135, for example, operates approximately 350 hours per year. A commercial transport, by comparison, might fly eight times as many hours in a year.

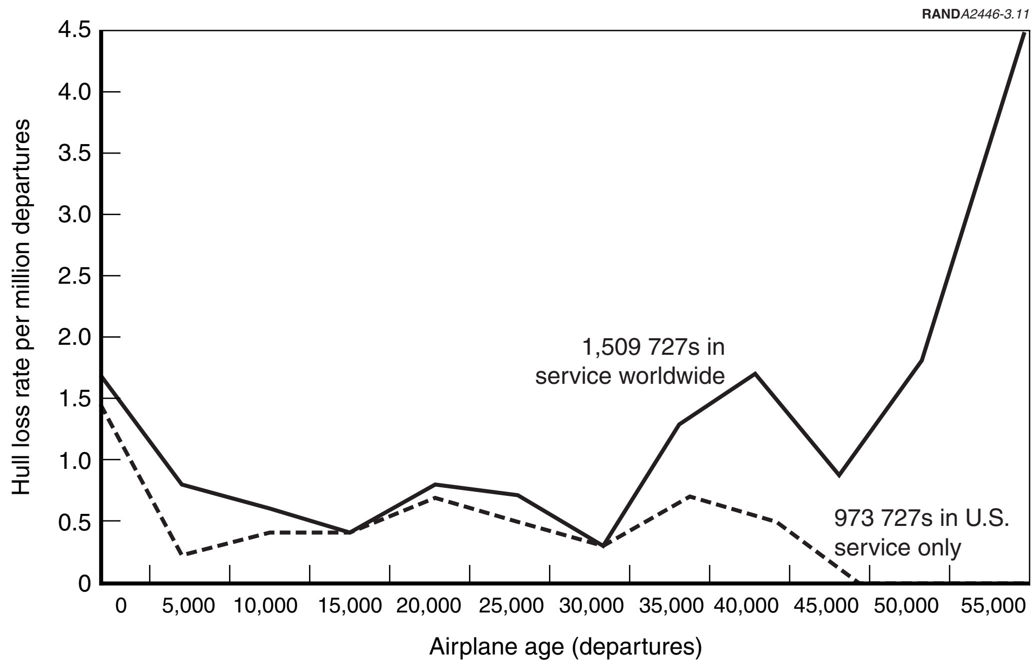
checks in the commercial fleet.[25] Although military overhaul and maintenance procedures have been curtailed in recent years, an aircraft completing an IRAN is, in many ways, restored to its delivery condition.[26] Air Force maintenance procedures are uniform, whereas considerable variation exists in airline maintenance procedures related to aging aircraft (DiDonato, December 4, 1997, p. 10).

To track the operation of individual aircraft, the Air Force also maintains a complex system designed specifically for evaluating maintenance requirements. This system, the Aircraft Structural Integrity Program (ASIP), closely monitors factors that affect the aging of an individual unit in the Air Force fleet (Giese, April 1998). The service history and flight profile of each aircraft are combined with information related to structural repairs on the airframe, inspection results, and maintenance history. The system compares analytical results against a baseline of structural and performance capabilities supplied by the aircraft manufacturer. The resulting quantitative foundation allows inspection and maintenance procedures to be tailored to individual aircraft.

Although maintenance procedures and the approach to dealing with aging systems in the military differ from those in the commercial world, available data indicate that aging has not yet become a significant safety problem in the airline industry. Figure 3.11 shows the hull loss accident rate for the popular Boeing 727 aircraft. For the venerable 727, the domestic accident rate has actually dropped to zero. The rising worldwide accident rates probably reflect the operation of these

[25]Airline maintenance is allocated in a sequential series of checks, beginning with visual “A” checks at 100 hours, “B” checks at interim frequencies, “C” checks occurring approximately every 1,500 hours or annually, and “D” checks at 18,000 hours. Both “C” and “D” are considered heavy maintenance. The “D” check is a depot maintenance procedure that includes significant teardown of the aircraft, structural sampling for corrosion and cracking, detailed systems testing, and the replacement of worn components.

[26]The IRAN process has been replaced by programmed depot maintenance (PDM). Earlier RAND research concluded that many of the repairs performed during PDM could be performed at the aircraft’s base. Over time, Air Force PDM requirements have generally lengthened the PDM requirements for aircraft (Donaldson and Poggio, November 1974).



SOURCE: From Boeing Commercial Airplane Company, based on actuarial data from Airclaims, Ltd.

Figure 3.11--B-727 Hull Loss Rate by Aircraft Age

aircraft in environments with less rigorous maintenance procedures, fewer navigational aids, and flight crews with less training.

The 1988 accident of Aloha Airlines Flight 243 near Maui, Hawaii, focused attention on widespread fatigue damage (WFD) (National Transportation Safety Board, June 14, 1989). A growing body of evidence is now making clear that aging effects are not limited to WFD. The performance of engines, avionics, and other flight systems is also affected by age, a fact suggested by the TWA Flight 800 crash. The ongoing investigation has already caused a fundamental shift in thinking about the contributing factor that aging *systems* add to the operational equation. The issue of electrical wiring deterioration in older aircraft is a case in point. Bundles of electrical wires could potentially be exposed to chemical attack, chaffing, damage caused by maintenance and modification, and temperature extremes.[27]

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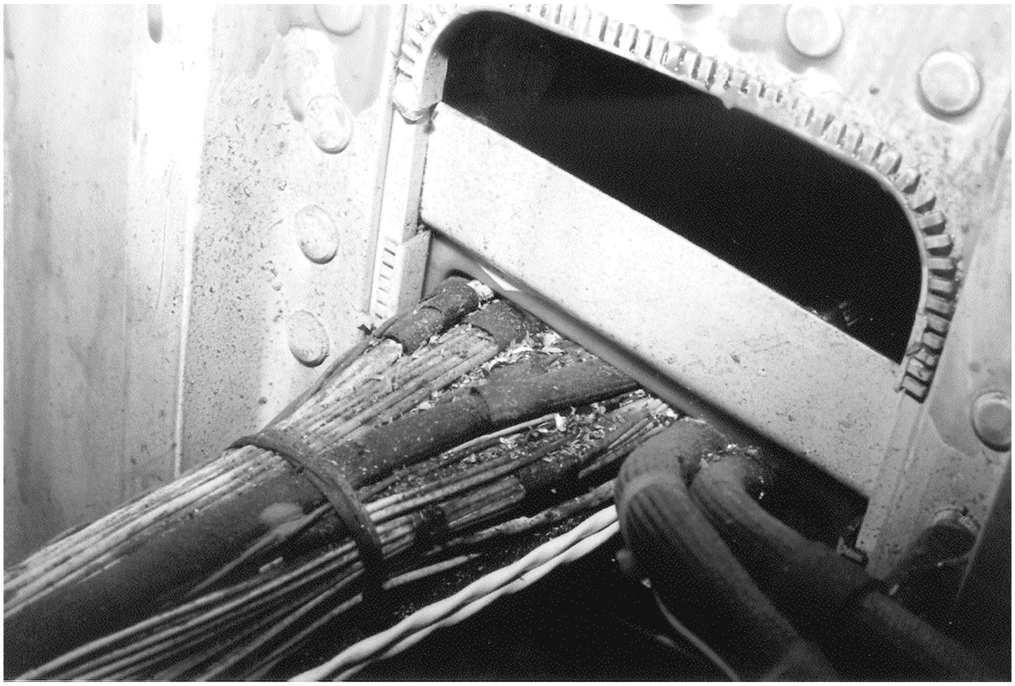
[27]Repair, modification, and alteration of the airframe often involve drilling into aluminum sections. Falling debris in the form of metal chips has been found to cause significant damage to wiring bundles



SOURCE: Photo courtesy of NTSB Major Accident Investigations Division

Figure 3.12--Wiring Deterioration in Older Aircraft

As Figure 3.12 shows, significant deterioration in the integrity of wiring can occur during normal operation. Similar deterioration can also occur in aircraft hydraulic systems.

Most research conducted to date on aging aircraft and their systems quite naturally focuses on first- and second-generation airliners; comparatively less is known about how more-complex aircraft will age. First- and second-generation airliners with servomechanical control systems and limited integration between systems may age more gracefully than newer aircraft equipped with fly-by-wire systems, composite structures, and highly integrated systems.

Although many aviation experts express concern about the operation of aging aircraft, insufficient evidence exists to predict an increased accident rate based on age alone. The airline industry suffers from a lack of quantitative data on which to build trend indicators in relation

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over the long term. This and other problems were addressed in wiring-related recommendations made by NTSB Chairman Jim Hall to FAA Administrator Jane Garvey on April 7, 1998, calling for stepped up inspections and repair.

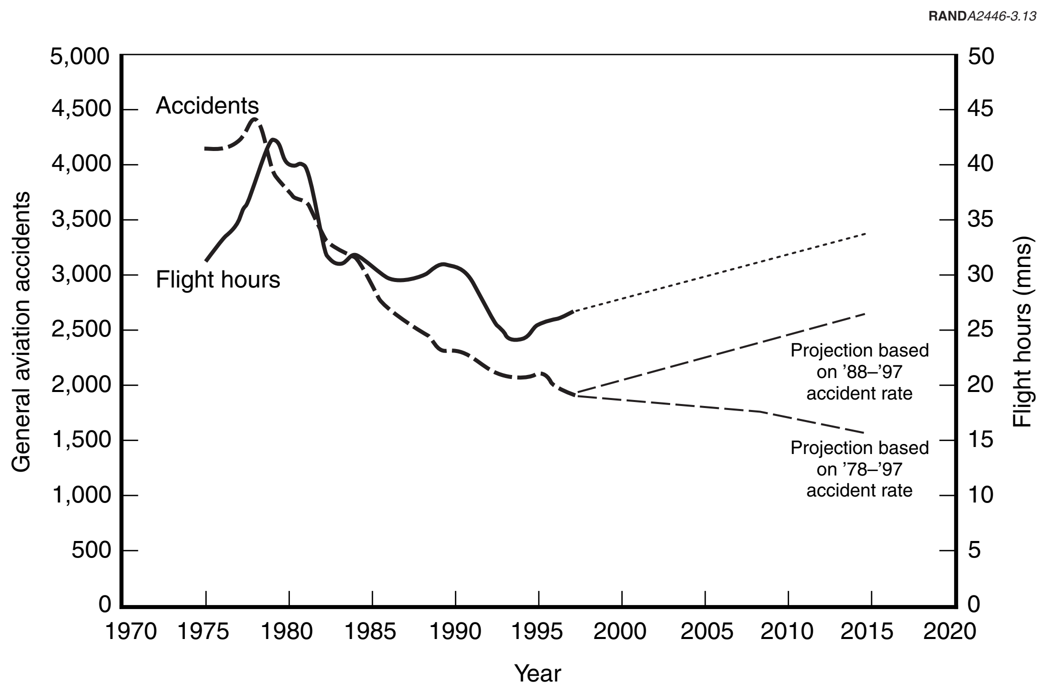
to aircraft aging. For the Air Force, with a fleet of more than 16,000 aircraft, programs such as the ASIP are a viable investment. However, it is more difficult for individual airlines to justify such investments. Without a rich data environment, the correlation between aging and incident/accident rates is unclear. The FAA's National Aging Aircraft Research Program has linked with the Air Force's Aging Aircraft Program Office and NASA's Aging Aircraft Program in an attempt to answer questions related to the effect of age on an aircraft's flight-worthiness.

It is reasonable to expect that the NTSB will experience some increase in incident reports related to events involving aging aircraft and systems. Monitoring events involving aging aircraft should continue to be a high priority within the NTSB. Future incident and accident investigations should attempt to quantitatively establish any emerging trends in this area. The Safety Board also has gained extensive experience with aging systems and has the ability to communicate knowledge and findings to the broader research community through the means of a safety study.

TRENDS IN GENERAL AVIATION

More than 180,000 GA aircraft are in active operation in the United States today. As discussed in Chapter 1, the NTSB currently investigates approximately 2,000 GA accidents each year through its six regional offices and four smaller field offices. This is a very significant factor in the workload of Safety Board investigators and managers. GA flight hours are expected to increase steadily. Reform of liability laws, the current strong economy, and the growing popularity of aviation as a sport have combined to cause a renaissance in GA, reversing a 15-year decline. The projected growth in GA is shown in Figure 3.13 alongside the historical and potential future accident rates.

If the GA accident experience of the past decade occurs in the future, GA accidents could increase as traffic grows. But, if the cumulative accident experience of the past *two* decades applies, the



SOURCE: Developed from the NTSB Aviation Accident Data Base; and FAA, *Long-range Aviation Forecasts,* June 1998.

Figure 3.13--GA Demand Forecast and Historical Accident Rate

number of accidents could decline. There is no way to definitively assess the future GA accident trend, although we can observe that although the GA accident rate is at its lowest point in history, the rate of decline has slowed and has been relatively flat in recent years.

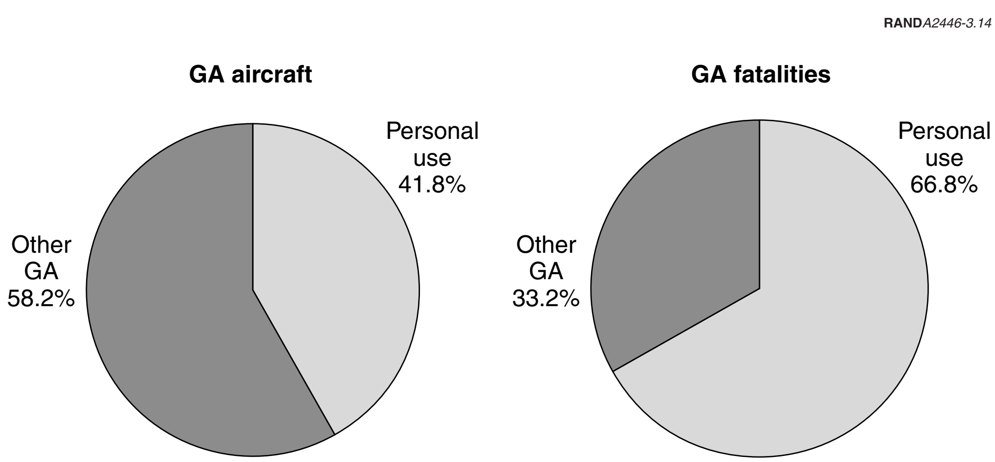
Most of the R&D investments in aviation safety are focused on the air carrier aviation segment. Only modest investment is directed at safety improvements for GA aircraft. This places the burden of further reducing the GA accident rate largely on industry and association initiatives. If such initiatives are not successful, the GA accident rate could rise in proportion to increased flight activity.

Factors other than flying hours alone will impact the nature of GA accident investigations in the future. The variety of air vehicles that will be operating and the amount of technology being integrated into new designs are both growing dramatically. The most significant factor likely to affect the NTSB in the coming years, however, is growth in the number and diversity of personal use aircraft.

As shown in Figure 3.14, personal use aircraft, in addition to being the largest single segment of the GA population, generate more than their share of fatal accidents. Most of these accidents have unremarkable causal trails, but the NTSB is legally obligated to investigate them and to issue reports. A small, but important, percentage of these accidents lead to the identification of significant safety issues and the issuance of industry-wide recommendations.

The diversity of aircraft in the personal use segment is shown in Table 3.2. The personal use category encompasses a wide range of aircraft, from the popular Cessna, Piper, and Raytheon-Beech single and light-twin aircraft, to retired military fighters and trainers, to ultralights.

The diversity of GA aircraft places heavy demands on the skills and experience of NTSB accident investigators. For example, the number of former military aircraft, or “warbirds” as they are called, is steadily growing. In recent years, the warbird segment of GA has expanded to include jet aircraft, some of them capable of supersonic flight. These jets are usually high-performance aircraft designed to meet military standards. GA pilots transitioning to warbirds are often unprepared for the challenge of flying powerful, and in most cases, much less forgiving aircraft. The investigation of an accident



SOURCE: Aircraft Owners and Pilots Association, July 1998, p. 13.

Figure 3.14--Personal Use Aircraft as Percentage of GA Aircraft and GA Fatalities

involving a retired fighter aircraft requires investigators to understand military systems, often of foreign manufacture, that are several decades old.

Table 3.2

Diversity in the Personal Use Aircraft Segment

Type	Approximate Number
Manufactured light	63,000
Single/Twin	
Vintage/Antique*	36,200
Warbird	4,300
Aerobatic	900
Kit/Homebuilts	10,300
Ultralights	4,600
Lighter-than-air	2,100
Gliders/Parasails	2,100
Rotorcraft	1,500
Total Personal Use Aircraft	125,000

*Aircraft manufactured before 1960.

SOURCES: Federal Aviation Administration, February 1995 and May 1999b; General Aviation Manufacturers Association, 1999; Experimental Aircraft Association Web site (www.eaa.org); Aircraft Owners and Pilots Association Web site (www.aopa.org).

At the other end of the spectrum are kit and homebuilt aircraft. In many respects, these aircraft represent the leading edge of GA aircraft technology. Because these aircraft utilize technology not yet incorporated in production units, the pilot is in essence operating an experimental aircraft, assuming the dual roles of test pilot and flight test engineer. These aircraft often are constructed of advanced composites, use state-of-the-art avionics, and operate with high-power loadings.

Many kit and homebuilt aircraft employ custom fuel and electrical systems, extensive modifications to design plans, and material substitutions. Powerplant technology also varies widely. While most kit and homebuilt aircraft utilize modified air-cooled aircraft piston engines, many are transitioning to converted automotive, modified snowmobile, and even rotary and diesel engines. In short, very little standardization exists in this segment of aviation.

Sport flying attracts many famous individuals, and accidents involving public figures generate significant national media attention. The deaths of singer-actor John Denver in a homebuilt aircraft and former Air Force General David McCloud in a foreign-made aerobatic aircraft are examples of GA accidents that require extra efforts on the part of the NTSB. The 1999 loss of John F. Kennedy, Jr., and members of his family led to an investigation rivaling that following a crash of a large commercial airliner.

Safety is the primary concern for the future of GA. More than 90 percent of the accidents tracked by the NTSB are in the GA segment, and nearly half of the recorded GA accidents are traced to failures of the flight crew. Flight crew training is therefore a major focus of the FAA's General Aviation Accident Prevention Program. Safety education is also vigorously pursued by organizations representing GA, most notably the Aircraft Owners and Pilots Association (AOPA), which hosts the Air Safety Foundation, and the Experimental Aircraft Association (EAA). The EAA operates a network of affiliate organizations, such as Warbirds of America and the Vintage Aircraft Association, which also conduct safety programs targeted at their flying communities. For example, the numerous warbird accidents have prompted the community of warbird operators to institute an array of safety programs and workshops to promote safer operations.

Another important factor related to safety is that GA flying often occurs in uncontrolled airspace. Historically, high equipment costs have prevented GA aircraft from making use of the extensive radar services currently available. The planned transition to free flight, however, requires more extensive integration of GA aircraft into the airspace system. The advent of GPS, in addition to the development of lower cost, high-reliability electronics, promises to make CNS services more broadly available to the GA community. The FAA, NASA, and avionics manufacturers are cooperatively exploring revolutionary new low-cost systems to automatically alert pilots of traffic conditions and provide cockpit displays showing the flight patterns of other aircraft.

Through these many initiatives, it is probable that GA safety will continue to improve, but the NTSB will likely continue to investigate a large number of these accidents. However, the NTSB’s workload will not be affected solely by an increased number of accidents. As with commercial aircraft accidents, investigators will likely face increasing diversity and complexity with GA accidents. The NTSB will be forced to develop new methods of managing the GA workload that ensure both efficient use of staff resources and thorough investigations.

NEW USERS OF THE NATIONAL AIRSPACE SYSTEM

A variety of new vehicle types could become operational during the first decade of the twenty-first century. Because these vehicles will share the civil airspace with other aircraft, NTSB will need to follow their evolution and ultimately become familiar with their designs and operations.

Unmanned aerial vehicles (UAVs) are expected to become more important to U.S. military operations over the current decade. Many of these vehicles are capable of extremely long-range, long-endurance operations (Munson, April 1999). The Teledyne-Ryan Global Hawk, for example, has an operational radius of 3,000 nautical miles and can remain aloft for 24 hours at that radius.

During limited periods of training and deployment, military UAVs will have to share the civil airspace with other aircraft. Public and commercial users also have an interest in exploiting the capabilities of UAVs. Television news organizations, for one, see great potential for traffic monitoring and special event coverage. Long-endurance aircraft platforms, currently under development for use as Internet relay platforms over populated areas, may ultimately evolve to include unmanned aircraft (Platt, June 1999, p. 151).

The DOD is currently working with the FAA to define operational procedures for safely handling UAVs. Integration of commercial systems into UAV platforms is still on the horizon. Resolving these UAV issues with the FAA and its counterpart international organizations is essential to successful realization of the UAVs’ potential. Accidents involving most major UAV designs have already occurred, although to date they have occurred either on military test ranges or in combat operations and have not involved manned aircraft.[28]

Other new vehicles will begin using the civil airspace. Tilt-rotors, such as the Bell Helicopter Textron 609 civil tilt-rotor, represent a new class of aircraft, combining aspects of fixed and rotary wing aircraft. The aircraft is scheduled to fly in 2001 and enter service in 2003 ("Mating Season," October 2000).

Also proposed are manned and unmanned commercial reusable launch vehicles (RLVs). These vehicles are being conceived to deliver payloads to low earth orbit (LEO) and then reenter the earth's atmosphere to perform controlled landings for subsequent reuse.[29] The FAA Office of Commercial Space Transportation has already issued interim safety guidance for these vehicles (Federal Aviation Administration, January 4, 1999). Several approaches for integrating these vehicles into the NAS are under study.

The future of these new reusable commercial vehicles is very uncertain. Some candidate commercial systems, originally scheduled to enter service in the near future, have succumbed to developmental problems, funding shortfalls, or a lack of demand. The marketing problems experienced by LEO telecommunication satellite companies have in particular influenced the decision of many launch system developers to cut back on ambitious deployment plans.

Many of the systems discussed here present long-range issues for the NTSB to contemplate. The NTSB has so far tackled few investigations related to advanced aerospace systems. Planning for new types of operations should be an increasingly important factor in Safety Board training practices in the future.

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[28]Following a March 19, 1999, crash of the Air Force's Global Hawk UAV, the FAA rescinded its certification to fly in commercial airspace (Whitley, April 30, 1999a). The FAA subsequently cleared the Global Hawk to resume flight testing in May 1999 (Whitley, June 4, 1999).

[29]An optimistic summary of the many RLV concepts currently under consideration can be found in Federal Aviation Administration, May 1999a.