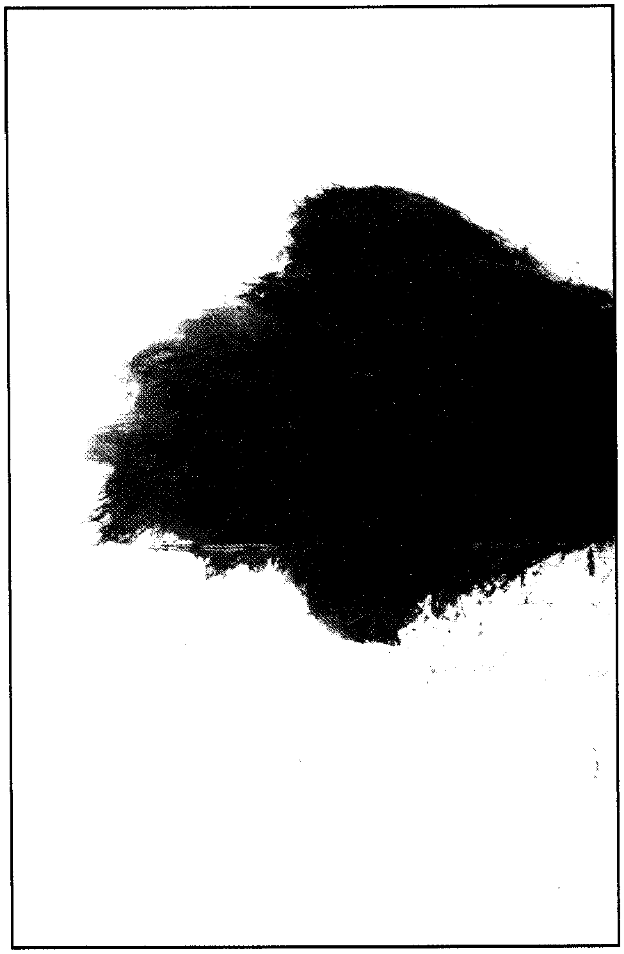

# Fire Research Plan

**January 1993**

U.S. Department of Transportation
**Federal Aviation Administration**

**FAA Technical Center**
Atlantic City International Airport,
New Jersey 08405

# FOREWORD

Improved aircraft fire safety has always been an important FAA goal. Regulations in support of fire safety are a result of continuous research, testing, and evaluation efforts based on service experience and the introduction of new technology.

In order to meet safety needs in the twenty first century and substantially improve fire safety, new research initiatives are needed that are fundamental in nature and long-range in perspective. This dramatic change to a long term fire safety focus resulted from Public Law 100-591, the Aviation Safety Research Act of 1988. This legislation mandates that the FAA establish long-range research programs in a number of critical areas including fire safety.

This fire research plan represents the first comprehensive attack on future aircraft fire safety problems with an eye to the enabling technologies that can eliminate them. This plan was developed under the guidance of and with inputs from technical specialists in other government agencies, national laboratories, universities, and industry.

I am confident that the research conducted according to this plan will lead to a demonstrable improvement in aircraft fire safety and provide spin-off technology for non-aviation use as well.

Harvey B. Safeer, Director
FAA Technical Center

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# EXECUTIVE SUMMARY

The goal of the Federal Aviation Administration's (FAA's) fire science program is to eliminate fire as a cause of fatalities in aircraft accidents. The legislative impetus for this program is Public Law 100-591, the Aviation Research Act of 1988. This Act mandates the FAA to perform the long-range research that will lead to new technologies for improving aircraft fire safety. Achieving the research goal requires both advances in fire science and the development of new electronic, chemical, and material technologies to implement safety improvements.

Long-range improvements in aircraft fire safety clearly demand more fire resistant materials, safer fuels and fuel systems, better fire suppression and extinguishment, and advanced systems capable of maintaining a habitable cabin environment in the event of an accident. However, it is not now known how much more material fire resistance is needed, and how this need is to be quantified. Nor is it known what specific changes would make a fuel safer, and how the improvement would be quantified and verified. These unknowns exist because, at this point in time, there is no comprehensive method available to quantify how much improvement is needed in each area and how well a specific technique can provide that improvement.

Due to the range of conditions associated with aircraft fires, experimental determination of the effects of dominant parameters is impossible. Analytic models are needed to predict the dynamics of the fire and fuselage interaction. This modeling capability will provide the basic tool for analyzing risk and vulnerability, which will allow for the identification of weak links that increase vulnerability to fire. These tools will also allow for analysis of the effectiveness of improvements and a determination of when fire safety improvements reach the point of diminishing returns.

The FAA's fire research mission is aimed at aircraft safety improvements and its research is product oriented. The basic research component is aimed at those areas needing advancement so that specific safety improvement possibilities can be defined. The long-range research applied component is directed at developing those improvements. The FAA fire research areas are:

- Fire Modeling
- Vulnerability Analysis
- Fire Resistant Materials
- Improved Systems
- Advanced Suppression
- Fuel Safety

Organizing the program along these lines will allow research activities and findings from other organizations to be added to the FAA program without any duplication of effort.

Long-range research will focus on both current and future aircraft. From a fire analysis perspective, all current production large transport category aircraft share major design commonalities, which may not apply to future designs. High speed civil transports will have a fuselage structure that is titanium or composite rather than aluminum. Future fuels such as hydrogen present fire threats totally different from those of current jet fuels. The technical products of the research will include:

- new fire safety design tools,
- new technology safety products,
- more economical fire suppression systems,
- ultra-fire-resistant materials,
- tailored fuel properties, and
- advanced fire safety assessment technologies.

The science and technology developed to meet the goal of eliminating aircraft fire fatalities will spin off into many areas of transportation, industry, and commerce. Aviation has such critical requirements for light weight, minimum space, high efficiency, and extreme reliability that successful aircraft fire safety improvements will find ready application outside of aviation.

# 1 AIRCRAFT FIRE SAFETY

The goal of FAA's fire science program is to eliminate fire as a cause of fatalities in aircraft accidents. Major advances are needed to develop technologies for fire safety assessment; for totally fire resistant aircraft cabins; for fire safe fuel systems; and for smart fire control and extinguishing systems.

Scheduled airlines represent the most reliable, safe, and fast way to travel long distances. Safety results from either preventing accidents, e.g., mandatory ground proximity warning systems, or designing the aircraft to make unavoidable accidents survivable, e.g., seat strength standards.

Any airplane crash poses the threat of fire. Due to the magnitude of aviation kerosene carried by large jets (up to 57,285 gallons in a Boeing 747-400), a post-crash fire can be severe and deadly. The high heat release of a post-crash fuel fire can melt the fuselage skin within a minute, and then ignite interior cabin materials. The post-crash fire incidence rate can be decreased by fuel systems designed to minimize ignition sources. Passenger survivability can be increased by the use of low flammability cabin materials. Even though accident rates may be low, major post-crash fatal fires are possible whenever an accident involves a fuel system failure. The potential for loss of life grows with the number of passengers carried, and with the trend toward larger aircraft, each accident will endanger more lives.

Fatalities directly resulting from inflight fires are rare. The life threatening aspect of such fires is associated with the time required to descend and safely land the aircraft: from minutes for flights over land, to hours for flights over water. The descent and landing time provides an opportunity for small inaccessible fires to grow to a point where either the integrity of the aircraft or the lives of the passengers are imperiled. There are design features and procedures now in use which can prevent or control inflight fires: wire insulation flammability requirements; cargo compartment liner fire test standards; fire extinguishing systems; and circuit breaker reset procedures. Inflight fire and smoke incidents that do not cause injury or damage are commonplace. There were 892 such incidents in the free world civil fleet between 1974 and 1989. Only twenty of these progressed to the level of accident.

Achieving the FAA's fire research goal requires advances in both fire science and the use of new electronic, chemical, and material technologies for aircraft fire safety improvements. Fire science is different from the more commonly practiced field of combustion science, which deals with *controlled* chemical reactions that liberate energy in the form of heat, e.g., jet engines, welding torches. Fire science deals with *uncontrolled* reactions that are usually unwanted and destructive. The state-of-the-art in combustion science is about 20 years ahead of fire science. One likely reason for this lead was the Department of Defense concentration on the long-range combustion research needed to develop propulsion systems for advanced weapons. Fire research has never had this kind of investment driver. Advances in fire science in the last 20 years have come from limited fundamental research into the characteristics and behavior of fire. The reality is that there has never been a long-range fire research program with sufficient funding to parallel the progress made in the combustion field. In the area of aircraft fire safety, the FAA is now initiating such a long-range program; this document is the first product of that program.

The science and technology developed to meet the goal of eliminating aircraft fire fatalities will be applicable to other modes of transportation, industry, and commerce. Aviation's requirements for light weight, minimal space, high efficiency, and extreme reliability will ensure that aircraft fire safety improvements find ready application outside of aviation.

## 2 FIRE RESEARCH MISSION

The FAA's fire safety research and development mission was significantly broadened by recent legislation. Prior to 1988, Section 312 of the Federal Aviation Act of 1958 authorized the FAA to "undertake or supervise such developmental work and service testing as tends to the creation of improved aircraft, aircraft engines, propellers, and appliances." This language directed FAA research toward applying technology, emphasizing engineering development, and testing and evaluating available devices and materials.

Public Law 100-591, the Aviation Safety Research Act of 1988, amended Section 312 of the Federal Aviation Act 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 materials 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 post crash fire hazards." This Act directs the FAA to perform comprehensive research in identified areas, which include a number of fire safety thrusts.

Further insight into the intent of Congress can be found in the Act's companion House of Representatives Report 100-894. The Office of Technology Assessment is reported to see a "need for careful research to evaluate potential crash and fire safety technologies ... improved fire- and smoke-resistant materials for aircraft interiors, improved smoke detection and fire containment systems (particularly for in-flight fires), automated systems to aid pilots in detecting and responding to in-flight fires, and advanced fuels with low flammability." The companion report states the "FAA should work toward a goal of a totally fire resistant cabin, or a cabin where survivors of a crash would have five or ten minutes to evacuate the cabin." The report also states that this research should emphasize emerging new technologies to achieve this goal.

The 1988 Act defines long-range research as those discrete projects unlikely to result in initial installation of improvements within ten years. The companion report states that "Part of the reason for the long-term emphasis in the authorization section of the bill is to allow the FAA to attract and retain experts ..." The companion report further explains the requirement for research planning and structuring as a way to allow the public to see programmatic opportunities resulting from increased research funding, and "...intends the FAA, in administering the program, make optimum use of the capabilities in other government agencies...in colleges and universities, and in the for-profit and not-for-profit institutions of the United States."

## 3 RESEARCH NEEDS

Long-range improvements in aircraft fire safety clearly demand more fire resistant materials; safer fuels and fuel systems; better fire suppression and extinguishment; and advanced systems capable of maintaining a habitable cabin environment in the event of an accident. However, it is not now known how much more material fire resistance is needed and how this need is to be quantified. Nor do we know what specific changes would make a fuel safer and how the improvement would be quantified and verified. These unknowns exist because at this point in time there is no comprehensive method available to quantify how much improvement is needed in each area and how well a specific technique can provide that improvement.

Historically, aircraft fire safety testing relied on test scenarios. The effectiveness of new improvements for real accidents is still a matter of conjecture. However, there has been a measurable increase in fire safety for accidents that are similar to the test scenarios. The safety advances have resulted from near-term research based on service experience problems and applications of existing technology. This near term research and development has been successful and will continue.

Real accidents exhibit variations in dominant variables that affect the growth and severity of fires; e.g., wind speed and direction, fuselage integrity, fuel fire location, and fuselage door openings. The large number of dominant variables leads one to conclude that an experimental program to determine their effects on aircraft fires would be an enormous effort. A fire test facility would be needed that could expose various fuselages to large fuel fires under controlled wind speed and direction conditions. There is presently no such facility. To design and build such a facility would take a decade and cost tens of millions of dollars. The sequential testing of complete fuselages for a number of wind conditions, to produce a baseline, and the subsequent testing of new materials and design improvements would take another decade and require enormous funding.

Recent advances in computer technology indicate that an analytical model can be developed to predict the dynamics of a fire and its effect on an aircraft across wide ranges of the dominant variables. The availability and low cost of "super-computer" time, due to the recent downturn in defense related programs, makes this analytic approach even more attractive.

The modeling effort can also provide the basic tools for an aircraft fire risk and vulnerability analysis with a resulting technology that can be used to predict the safety of a given aircraft design. This technology has direct application to both in-flight and post-crash fire threats. Exercising the aircraft fire analysis tools will identify weak links that increase vulnerability to fire. These weak links will show where improvements are needed in existing materials, structures, or systems. Shortcomings in cabin material flammability properties could lead to a specification that would make the aircraft interior totally fire resistant in accidents. Other weak links might be in design deficiencies that can be cured by the application of new fire protection systems. The analytic tools can also provide the capability to determine when fire safety improvements reach the point of diminishing returns.

In addition to fire modeling and vulnerability analysis, the FAA's long-range aircraft fire program includes research in materials, fuel flammability, detecting and suppressing fires, aircraft cabin environment control, and integrating new technologies into an airplane fire protection system. These major thrusts cannot be done as stand-alone research efforts because the end products would be piecemeal and without trade-offs among the individual safety improvement areas. A critical challenge for the research team is to maintain a relationship among the research thrusts so that each is influencing, and being influenced by the others.

Long-range fire research will focus on both current and future aircraft. From a fire analysis perspective, all current production large transport category aircraft share major design commonalities, e.g., aluminum hulls, kerosene fuel systems, turbofan engines, and interior materials which meet current fire test specifications. Future designs are expected to differ significantly from current ones. High speed civil transports might have either a titanium or composite hull. The aluminum hulls now in service will eventually melt when exposed to an external fuel fire and the failure provides a path for fire to spread into the cabin. A titanium hull will not melt in a fuel fire. The titanium skin will get so hot that it will heat interior materials to the point where there will be a spontaneous internal explosion. A composite hull will burn, but its burning rate could be slow enough to provide the longest protection for the interior of the three hull materials. Some composites have the additional benefit of not only being good thermal insulators below their burning temperature, but of also forming an insulating, stable char as they burn.

High fuselage skin temperatures associated with supersonic flight have the potential for increased in-flight fire hazards. High residual fuel temperatures during descent and landing can also increase the post-crash fuel fire threat. The current fire safety design standards are based on over 30 years experience with the present aluminum hull fleet, and many have their origins in the era of reciprocating engines. Many of these standards are inappropriate for future aircraft designs. The analytic tools developed in this program will, for the first time, allow certification authorities to design and test standards in parallel with new aircraft developments.

# 4 RESEARCH ORGANIZATION

The way an agency organizes a research program usually reflects its mission. The National Science Foundation's mission is to develop new knowledge. Its fire and combustion work is organized by discipline, in a Chemical and Thermal Systems Division. A mission of the National Institute of Standards and Technology is to develop knowledge that can be used for fire safety improvements; its research is organized by subject. The FAA's fire research mission is aimed at aircraft safety improvements, and its research is product-oriented. Basic research is directed at those areas needing advancement in order to attain long-range safety goals. The FAA research areas are:

- Fire Modeling
- Vulnerability Analysis
- Fire Resistant Materials
- Improved Systems
- Advanced Suppression
- Fuel Safety

Organizing the program along these lines will allow research activities and findings from other organizations to be added to the FAA program without any duplication of effort.

Basic scientific progress usually results from the efforts of an individual researcher or of a relatively small team. This is true in the fields of fire and combustion. Verification of fundamental findings and the application of advanced technology usually involve significantly larger group efforts. A primary, and often unsuccessfully met, challenge in a long-range technical program is maintaining an optimal relationship between large and small program elements.

*Figure 4.1* illustrates how the program elements associated with in-flight fire must interact. Risk and vulnerability analyses are the drivers which point out technology gaps and provide the means to evaluate potential improvements. The thrust on

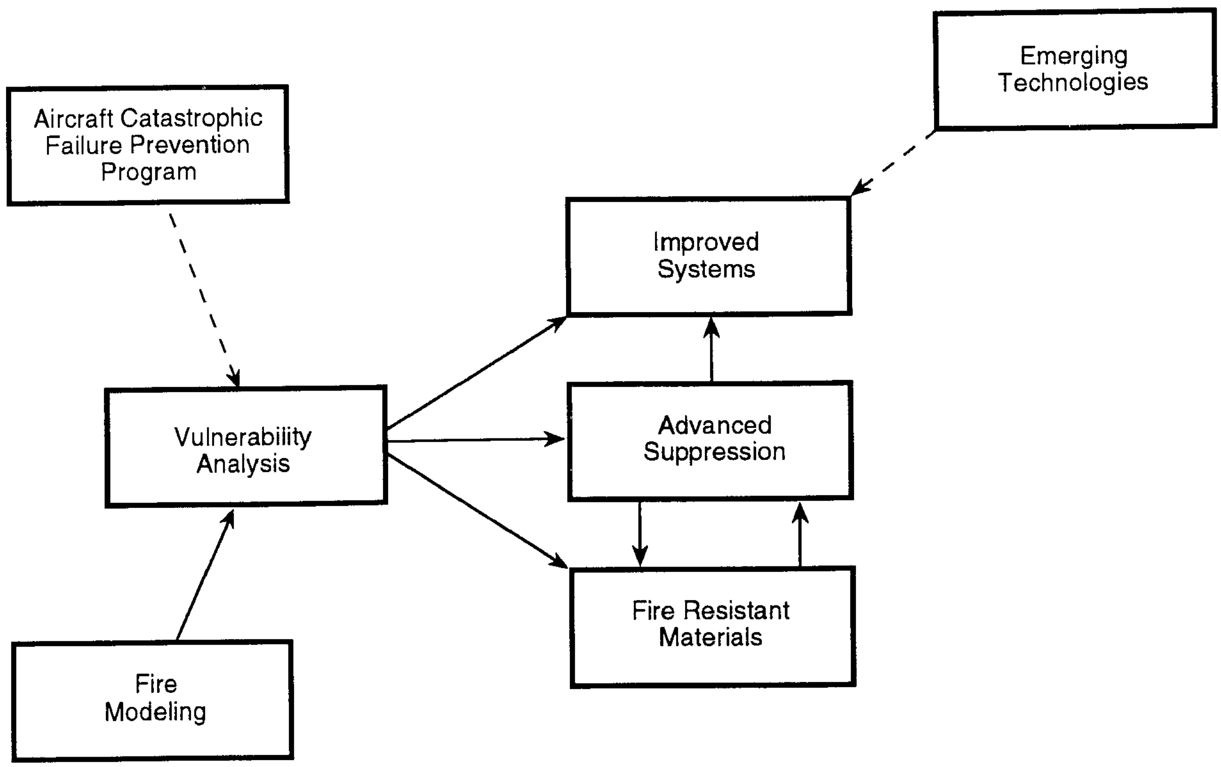


***Figure 4.1. In-Flight Fire Thrust Relations***

advanced suppression in this figure is extremely important because so much scientific information is lacking here. The relationships for post-crash fire safety are shown in *Figure 4.2.* The primary driver here is fire modeling, since significant advances are needed to understand a wide range of crash fire scenarios. The major safety improvements will come from advances in fire resistant materials and safer jet fuels. New technologies offer promising opportunities in the materials research area. New technologies for safer fuels are not obvious, which explains why fuel safety is still a high risk research area.

Within a technical area, the degree of coordination needed is subject matter dependent. On one end of the coordination spectrum is fire modeling which requires a high level of coordination among researchers so that their end product is a coherent and workable item. At the other extreme, developing improved systems may involve projects so unique that there is little or no relation to other projects.

This research plan stresses the development of analytic tools and improvements in materials and advanced systems. However, progress in these areas will demand substantial experimental support in order to gather input data for fire models and to verify fire model predictions. Experimentation will include physical fire modeling, material ignition and burning, suppression chemistry, combustion efficiency, and structural degradation. Test and evaluation of prototype improved systems and techniques will be performed by FAA staff who are now working in near term fire protection engineering.

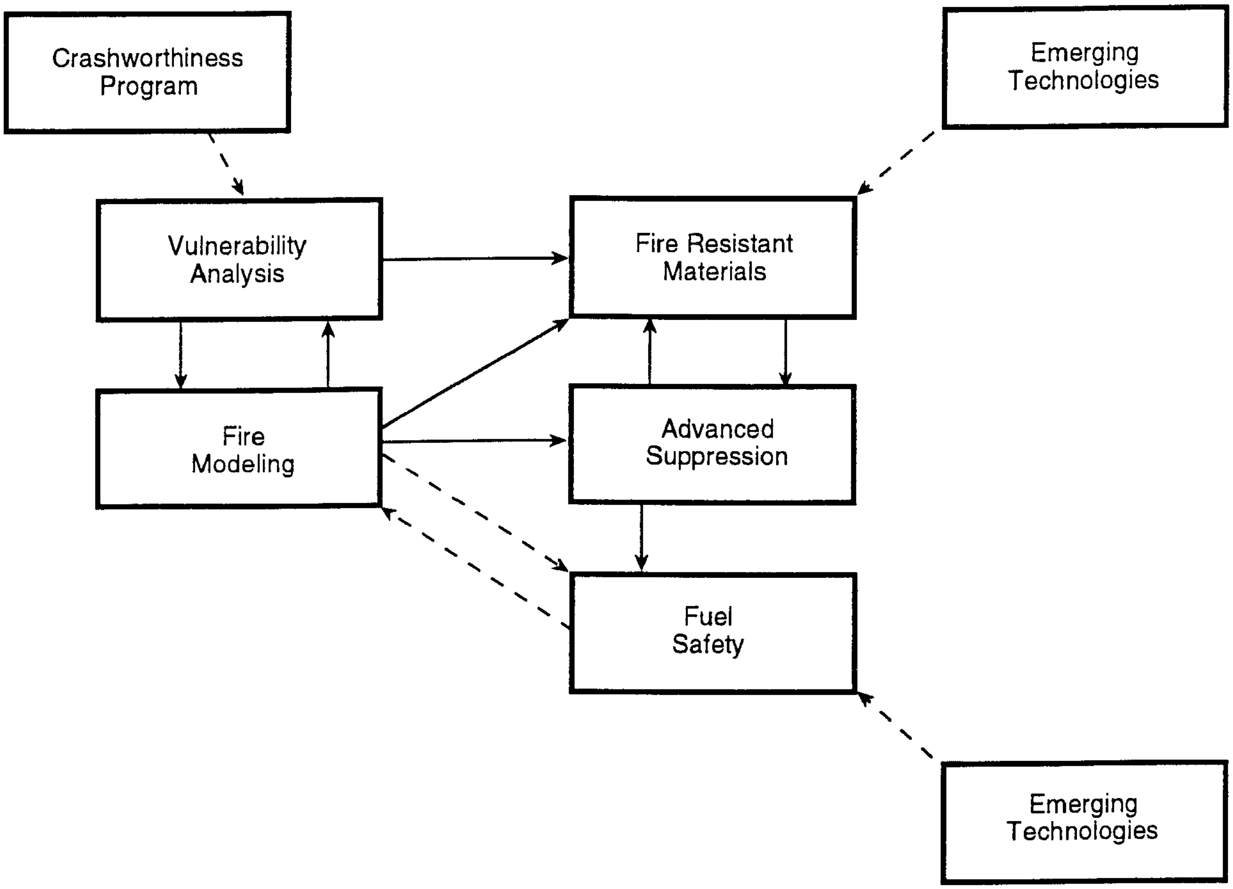


***Figure 4.2. Post-Crash Fire Thrust Relations***

Research coordination requires continual focus on the program goal, which is to save lives. The scientific objectives are to dramatically improve capabilities in fire modeling and suppression science. The product objectives are: improved fire resistant materials and structures, improved aircraft designs, development of advanced fire-safety systems, and low flammability fuels. Achieving the product objectives means using the technology now emerging from universities, industry, and other government agencies. After new safety products are developed from this research, their value in relation to cost can be determined.

# 5 FIRE MODELING

Research into predictive computer fire modeling for rooms, buildings, ships, and aircraft has been underway for more than twenty years. Earlier models were mostly zone models which use a combination of simple fluid flow equations and empirical fire correlations. Solving the equations simultaneously as a function of time yields information on temperature growth and smoke movement. The zone models are sensitive to the empirical equations they employ. More recent zone models have found additional use in litigation and building hazard assessment.

In contrast to zone models are field models, which solve complex fluid flow and energy transfer equations with detailed spatial resolution in enclosed or open spaces. Field models work from fundamental physical laws but their use was limited by a lack of computer capability and gaps in fire behavior understanding. Over the last decade, there has been sufficient progress to enable field modeling to address an increasing number of problems. Field modeling lends itself to aircraft interior fires because the number of different aircraft geometries is relatively small, and detailed information on the structure and content of the aircraft is available. With proper support, field models will become useful for aircraft fire prediction within the next ten to twenty years.

Field modeling will become more practical with increasing computer capabilities, such as parallel processing, and advanced understanding in fire physics and chemistry. These improvements will lead to the application of field models to aircraft fire scenarios that are entirely unlike those for buildings. A major modeling challenge is the burning of aircraft materials which are more complex than those that have been fire tested in the past. Burning aircraft materials can melt and flow, swell and intumesce, delaminate, and warp severely. With all the behaviors possible during fire exposure, there are unanswered questions on the usefulness of current standardized fire test methods for providing model flammability data.

The FAA pioneered the development of aircraft fire models in the 1970's, through a zone model known as DACFIR. Researchers at Thames Polytechnic recently used the PHOENICS field model to predict the effects of a simple, steady burning interior fire on the hazard development in a B737 fuselage. BP Ventures has been using Harwell Laboratory's FLOW3D field model to predict the effects of onboard cabin water spray systems to reduce the hazard of aircraft fires. Sandia National Laboratories has recently established a collaborative research program with SINTEF/Norwegian Institute of Technology to further develop and validate a SINTEF field model. *Figure 5.1* and *Figure 5.2* show the type outputs obtainable from this model. The figures represent a semi-trailer centered in a pool fire measuring 10 meters by 20 meters. *Figure 5.1* shows the gas flow field and the temperature distribution around and above the trailer approximately halfway along its length. *Figure 5.2* shows the fire's thermal radiation field around the rear half of the trailer near its bed. Although the Department of Energy, which sponsors this work, has weapon systems safety as a primary concern, the Sandia effort complements the FAA research program. The above three field model applications are limited to steady burning rather than growing fires, yet their ability to get spatial resolution in all three dimensions has proven to be their strength.

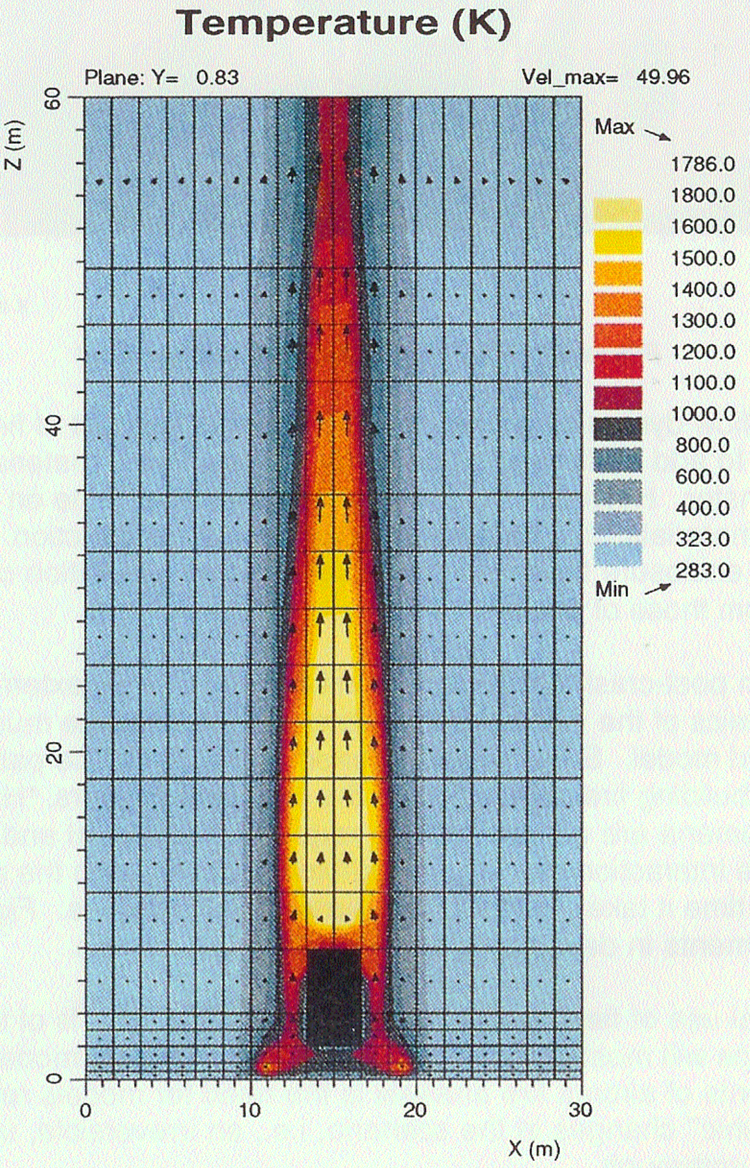


*Figure 5.1. End View: Temperature and Velocity Field*

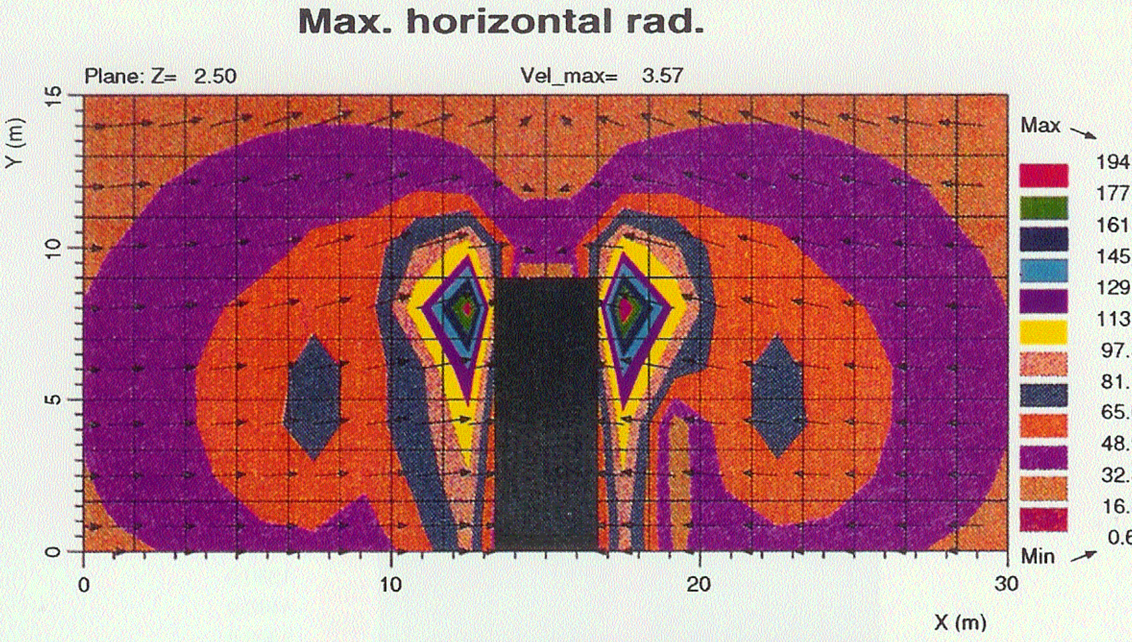


***Figure 5.2. Plan View: Thermal Radiation Field***

The treatment of flow dynamics is presently the strongest aspect of field models. Work is now underway to add realistic submodels for flame spread, material burning rate, and wall heat transfer. However, most earlier research was done on the burning of relatively simple materials which are not used in aircraft construction. Also, most field models deal with enclosure fires with configurations and ventilation conditions that are vastly different from those of aircraft.

The internal cabin post-crash fire is usually initiated by a large external, wind-blown fuel fire. The physics of the fuel fire penetration into the fuselage must be included in an aircraft fire field model. Some of the required research can be patterned on methods used in building fire research over the past twenty years. However, some aircraft fire phenomena are unique and will require fundamental and unprecedented research, e.g., the interaction of a large wind-blown fuel fire with the aircraft fuselage structure and the time it takes to reach non-survivable conditions. *Figure 5.3* shows the role of experiments in developing and validating fire models.

While the potential use of field models alone looks bright, models of the complex post-crash fire scenarios will most likely be hybrids of field and zone models. One of the unique requirements of aircraft fire analysis is the need for models robust enough to handle "catastrophic" changes in the scenario, i.e., an irreversible, unstable change like a fuselage burnthrough.

Accurate predictive tools for aircraft fires are needed to establish where countermeasures can be most effective, what the countermeasures have to do, what design reconfigurations can improve safety, and what performance requirements would make interior materials virtually fire-proof. Without this FAA research thrust, the development of useful predictive tools for improved fire safety will simply not occur.

| | Research | Development | Application |
|---|---|---|---|
| **Modeling** | • Phenomenological model development, i.e., fire-physics and material models | • Integrated system model development | • Design definition tools |
| **Experiment** | • Phenomenological testing<br>• Model development data | • Model validation tests<br>• Proof-of-Concept tests | • System validation tests<br>• Regulatory test development |

***Figure 5.3. Role of Experiments in Model Development***

# 6 VULNERABILITY ANALYSIS

Aircraft fire risk and vulnerability research is needed for both in-flight and post-crash fires. The analyses are entirely different for these two types of fires. In-flight fires can involve failed systems as the ignition source or systems failure as a result of fire exposure. An example of this is the 1983 Air Canada accident where electrical load shedding and failures resulted in the engine high pressure bleed valve closing. As the aircraft descended, the closed valve prevented ventilation air from entering the passenger cabin.

Probabilistic Risk Assessment methodologies developed for nuclear power plants and weapon safety will be modified and applied to aircraft risk analysis. New methodologies developed for the FAA's Aircraft Catastrophic Failure Prevention Program will be used to evaluate the probability of a system failure as a fire source. Modeling techniques described in Chapter 5 will then be used to predict fire growth and vulnerability of exposed systems, materials, and structures. The fire involvement and energy contribution of potentially involved materials must then be determined. Recent risk analysis efforts in fire safety have already attempted to determine a reasonable upper heat release allowance for materials and assemblies involved in a realistic fire scenario.

In-flight fire vulnerability research can show what systems are most likely to cause a fire, what systems are likely to fail in a fire, and what fire scenarios are most likely to have catastrophic results. The conditional probability of a catastrophe then provides a basis for estimating fire safety of a given aircraft design. The relative magnitudes of the individual probabilities can be used to identify the design features, systems, and materials where improvements will be most beneficial.

While in-flight vulnerability analysis uses fire modeling as part of the overall hazard assessment, post-crash fire risk and vulnerability analyses will rely on the development of reliable and useful modeling techniques for post-crash fires. Because post-crash fire severity is strongly affected by wind direction, fuel spill amount and location, and fuselage structural damage, distributed probabilities have to be developed for a wide range of crash scenarios. Roughly half the fatal crashes involve fuselage separation, which is probably the most challenging element to be incorporated into post-crash fire models, and which strongly affects the fire involvement of cabin interior materials. Inputs from the FAA Crashworthiness Research Program will be used to develop a range of fuselage structural failure modes that may precede post-crash fire growth. As the modeling capability develops to analyze these scenarios and include the response of the aircraft structure to external and internal fire, major material and design vulnerability areas will be identified. Improvements can be developed and their effectiveness analyzed through the modeling process.

*Figure 6.1* and *Figure 6.2* show the relation of modeling to the development of Probabilistic Risk Assessment for both in-flight and post-crash fires. The figures also show how the influencing and emerging technologies relate to the Risk Assessment.

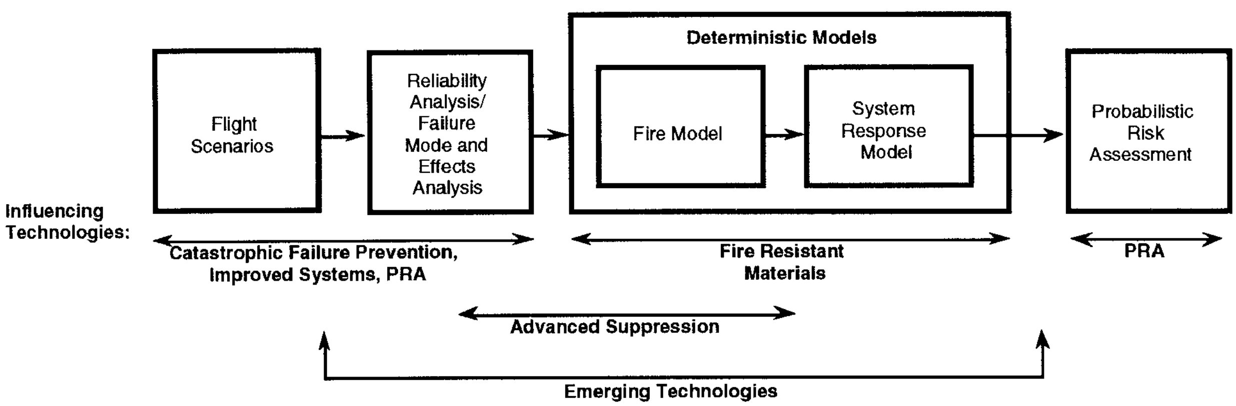


***Figure 6.1. In-Flight Fire Mitigation: Technical Approach***

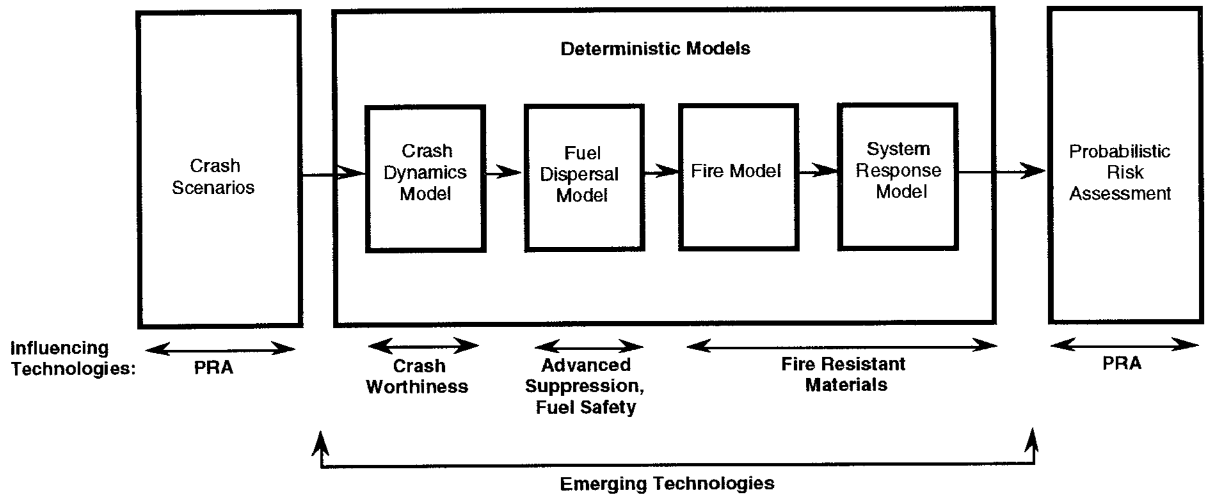


*Figure 6.2. Post-Crash Fire Mitigation: Technical Approach*

# 7 FIRE RESISTANT MATERIALS

Flammability requirements for transport category aircraft passenger cabins have become more stringent in recent years as a result of new regulations on seat cushion flammability and allowable heat release rates for cabin lining materials. Both regulations were based on full-scale fire tests that demonstrated that flashover in the cabin could be delayed if the heat contribution from burning interior materials was reduced. Research with the goal of a totally fire resistant cabin will develop new materials for seats and interior panels, and will consider the roles played by many other interior materials not affected by new regulations. Fire performance requirements for these advanced materials will come from the fire research findings and vulnerability analyses described in Chapters 5 and 6. These requirements amount to material specifications that need to be met for a "totally fire resistant cabin."

The new regulation on cabin panel heat release was proven to be a technology driver. However, there are newly emerging technologies that were not available for consideration when the panel regulation was under development. For example, in the early 1980's a class of polymer resins called cyanate esters was used primarily to make printed circuit boards. Now, a second generation cyanate esters has been developed with more versatile properties and better manufacturing characteristics. These materials and their future derivatives have great possibilities for cabin panels with improved fire resistance. New material development capabilities are appearing as experience is gained with blends of thermosetting resins, thermoplastics, and low temperature glasses. In part, this is due to the availability of new products that allow co-curing or co-processing of the material blend at temperatures at which the individual components are compatible. An example of this is a combination of thermoplastic and glass, where each have a softening or melting point at approximately the same temperature.

There is exciting new research underway at National Institute of Standards and Technology with the goal of relating polymer structure to material burning rate. In general, more polymer crosslinking and a higher percentage of molecular ring structure leads to lower heat generation by a burning polymer system. Also, chemical structures that degrade to a char during fire exposure can generate an insulation layer on the material surface. The insulation delays fire involvement of the polymeric material in the interior of the material. Examples of this are the phenolic resin heat shields on the Apollo spacecraft and the rocket engine nozzles in the Space Shuttle solid propellant boosters. The new technology which relates polymer composition and bond structure to fire performance provides for an equally new capability in which to design fire safety into polymer systems.

Flame retardents are extensively used now to minimize the flammability of organic materials. Halogenated additives have been widely used, since they are so effective in reducing ignitability. However, under severe fire exposures they may be relatively ineffective in reducing the heat output from the burning materials. New emphases on polymer products that can be recycled are also working against any increased utilization of halogenated additives. The non-halogenated group of fire retardents includes metal hydrates such as those containing aluminum, magnesium, and zinc. Many of these additives can yield char when used with polymer systems. Development of the technology to predict and optimize these additive effects would provide for an additional tool to design fire safety into aircraft materials.

Many small parts and accessories in the passenger cabin are now fabricated from thermoplastics such as polycarbonate and polyvinyl chloride, e.g., seatback trays, passenger service units, and window shades. These items are not covered by the regulation on heat release and smoke; consequently, their impact on aircraft fire severity is not known. However, just as new developments in polymeric resin technology offered improved fire resistance, new thermoplastic products and technologies offer improvement in the fire resistance of accessory parts. Technology for high temperature processing of thermoplastics and thermosets has advanced enough for these materials to be considered for the hull of the High Speed Civil Transport.

Three general approaches will be taken to develop fire resistant materials. Flammable gas produced by the material will be lessened by reducing its heating, using concepts like insulating and heat reflective coatings; dehydration of water bound in the material structure; and melting of high thermal stability crystalline polymers. The flammable volatile production from the material will be lowered by use of material formulations that either degrade to char or to a thermally stable ring structure with minimal evolution of combustible products. Material systems that can degrade to yield gases that act to suppress fire will be investigated.

Improved aircraft fire resistance requires research into fire effects on load-bearing structure. Many aircraft structures are assembled from different materials, and their arrangement can affect the total structure's response to fire. In such cases, improved fire resistance may demand that structural integrity be maintained during fire exposure.

In order for new fire resistant materials to be used, they must be practical and cost-effective. New production processes must be workable at the scale needed to outfit the civil fleet. End products must be light-weight, durable, and serviceable. Other functional specifications unique to the industry must also be attainable.

The fire resistance design goals for material systems will come from the fire modeling and risk analysis. There are enough newly emerging material technologies that achieving a "totally fire resistant cabin" now has a high probability of success within the next ten to fifteen years. But this will only happen if this stable and credible research program is initiated and sustained. The reality of this goal means that cabin materials will be developed which slow down ignition and flame spread so much that there is ample time for passenger escape. These materials will also find wide application outside of the aviation industry, enhancing the benefits of the research investment. However, without this dedicated effort, future material flammability improvements will be piecemeal, incomplete, and perhaps ineffective.

## 8 IMPROVED SYSTEMS

Complementing research on fire-resistant material systems is a research thrust to improve the fire safety of an aircraft's electrical and mechanical systems, e.g., in-flight smoke venting.

Achieving the goal of a totally fire resistant cabin will dramatically improve both post-crash and in-flight fire safety. However, flammability issues still remain with regard to luggage, freight, oxygen systems, flammable fluids, and trash. These items will remain as significant potential sources for smoke and toxic gases. Assuring passenger safety requires improved means to keep the flight deck and passenger cabin free of such noxious fumes.

The FAA has done considerable research on improving ways to keep the passenger cabin free of smoke. This work included studies, analyses, flight tests of alternate emergency procedures, and flight testing of aircraft with modified systems. Control of smoke, particularly buoyant smoke, in an aircraft has proven to be difficult. Unlike tall structures where the buoyant smoke's behavior can be used to eliminate it, the small diameter and horizontal attitude of a fuselage work against this type approach. However, recent FAA research has determined the type and magnitude of aircraft cabin flows that are required to control smoke. The flow of buoyant smoke along a cabin ceiling can be countered by a reverse axially directed ventilation flow of 100 feet per minute velocity. The main technology gap here is to develop a practical system that can do this. An accurate field modeling capability will be a tremendous aid to system design and optimization.

Results of risk and vulnerability analyses will also identify which of the "critical to flight aircraft systems" are most vulnerable to failure from exposure to fire or smoke. Improving the fire survivability of the most vulnerable systems improves overall flight safety most efficiently.

Opportunities for fire safety improvements due to the computerization of aircraft systems are continually emerging. The first generation prototype of an Aircraft Command in Emergency Situations (ACES) system was recently completed by the FAA. The prototype features include installation of additional and more advanced fire sensors in inaccessible areas, interfacing the sensors with flight deck computers, and use of an electronic checklist to guide the crew through appropriate emergency procedures. Future development of the ACES concept could incorporate artificial intelligence in the decision making process and employ neural networks to enhance the specificity of fire detectors. Advanced fire detection technology development will require a substantial experimental program to describe the fire "signatures" that the detectors must recognize. The fires of interest include both flaming and smoldering types. Improved fire detection requires both optimal fire recognition sensitivity and minimal generation of false alarms. Promising new sensor technologies for aircraft include thermal-acoustic and fiber-optic systems.

Permeo-selectric polymer membrane technology has advanced to the point where it is used to provide nitrogen enriched atmospheres for food preservation during shipment. Air is supplied to these membrane devices and it is then converted to two gas streams, one is nitrogen enriched and the other is oxygen enriched. Further advances in membrane technology could result in cargo compartment inert gas suppression systems and passenger emergency oxygen systems which would reduce the fire hazards from stored oxygen systems.

Emerging new technologies offer a multitude of opportunities for improved aircraft systems fire safety. Primary research will identify weak system links from the vulnerability analyses described in Chapter 6. Additional research will determine the best matched emergent technology, and tailor that technology to eliminate the weak link. Vulnerability analyses will be used to quantify the increase in safety from eliminating the weak link and to determine whether the approach is appropriate and worth pursuing.

## 9 ADVANCED SUPPRESSION

While combustion science is 20 years ahead of fire science, fire suppression science is 20 years behind fire science. In many fire problems, a theoretical solution or very good approximation is attainable because the gas phase reaction chemistry can be ignored. This is because the chemical reactions are very fast when compared to transport phenomena of heat transfer, mixing, diffusion, and flow. These latter parameters actually control ignition, fire growth, and energy release. Fire suppression involves the same transport phenomena plus gas phase chemical reactions. Additionally, the act of suppressing a fire disrupts the flow environment that the fire has created for itself.

Although some relatively simple suppression phenomena can be described theoretically, the vast array of existing and potential aircraft fire suppression techniques are based on trial-and-error development and testing. The manner in which water puts out fire is still a matter for speculation. Dry chemical powders are argued to extinguish fire by all types of competing and sometimes contradictory mechanisms. The behavior of chlorinated and fluorinated hydrocarbons, while easiest to understand, becomes problematic when real life installations are involved.

Since the science of fire suppression is so primitive, there is the possibility of tremendous technology improvements to be attained rather quickly. However, the technology gaps to be closed are extremely wide and there are many approaches to be pursued independently or in combination. The work on fire modeling and fuel safety can be used as a springboard from which to address the issues of reaction inhibition and process chaos. The work on fire resistant materials can be extended to look for interactions between aircraft materials and specialized suppressant agents. Emerging technologies associated with improved aircraft systems can be used to develop "smart" suppression systems that respond in ways tailored to specific fire signatures.

Developing a sound and useful science of fire suppression will require new discoveries and analytical techniques. While scaling laws and critical parameters have been found for the simplest reacting flows, the applicability of these laws and their derivatives to large and chaotic fire phenomena is unknown. Developing the envisioned advanced aircraft fire suppression systems of the next century is clearly one of the most complex and challenging thrusts in the long-range fire research program.

## 10 FUEL SAFETY

The major contributor to the post-crash fire hazard and loss of life is the burning of spilled fuel. Compared to any of the commonly used aircraft polymeric materials, aviation kerosene is easily ignitable, has high heat release potential, and possesses rapid fire spread characteristics. Large transport aircraft carry hundreds of thousands of pounds of jet fuel; a large burning spill can melt through the aircraft's skin within a minute. Actual passenger cabin survivability and escape times are strongly affected by fire location, fuselage door openings, fuselage orientation to the wind, fuselage separations, and whether the hull is in the spill or elevated on its landing gear.

A burning fuel spill is particularly dangerous because of its production and projection of radiant heat. Even materials that can resist ignition in an atmosphere of pure oxygen may burn readily when exposed to the radiant heat of a large fuel fire. Additionally, even if an aircraft cabin were totally non-combustible, there are scenarios in which hot combustion products from the burning fuel would enter the cabin so rapidly that there would be little time for escape. Reducing the fuel fire hazard is the most effective yet most difficult way to reduce aircraft fire fatalities.

Over the past forty years, many efforts have been initiated to reduce the number of post-crash fuel fires by improving aircraft designs to eliminate ignition sources for spilled fuel and also by reducing fuel flammability through the use of additives. In the 1960's, these experimental additives were aimed at making the fuel in the wings take the form of gels or emulsions. In the 1970's the focus shifted to the use of high molecular weight polymers that would prevent spilling fuel from forming highly flammable fine sprays. Small and intermediate scale tests usually demonstrated dramatic improvements in fuel flammability properties but full-scale airplane crash demonstrations resulted in dramatic failures of the additives. Additionally, almost all additives investigated in the past had significant incompatibilities with aircraft fuel systems. These problems were so serious that use of the additives by civil aviation might have resulted in a net increase in passenger fatalities due to increased accident rates.

The nature of the petroleum refining process precludes any drastic changes to overall chemical composition of aviation kerosene. Reducing fuel flammability requires one or more additives. Different additives can affect fuel flow behavior, break-up characteristics, vaporization, and surface characteristics. Use of these additives can make fuel ignition less likely or reduce the fuel energy release rate when ignition does occur. Some additives have been reported that reduce soot formation of burning fuel. These additives could conceivably reduce the radioactive energy output from burning fuel spills and reduce their impact on fuselage structure.

All major FAA efforts on fuel safety preceded the Aviation Safety Research Act of 1988, and were directed at the test and evaluation of experimental additives offered by the chemical industries. These programs had very little basic research content. As a result, the physics of post-crash fuel fire development is still poorly understood.

Development of a technical framework is necessary to find the parts of the process where intervention might be most effective. Spray combustion is one of the most complex and sophisticated subjects in engineering science. Theories and experiments generally deal with well-defined droplet distributions in fairly simple flow geometries. Modeling fuel release, break-up, and ignition while an aircraft is decelerating during a crash will be a major technical endeavor.

Long-range research will also address the safety impact of possible alternate fuels of the future, such as liquid hydrogen and shale derived hydrocarbons, as well as the fire threat associated with engines that operate on those fuels.

## 11 BENEFITS

The primary goal of and benefit from long-range aircraft fire safety research is the elimination of fire as a cause of fatalities in aircraft accidents. Achieving this goal over the next ten to twenty years will yield at least a tenfold benefit over the cost of the research itself.[1]

There are many ancillary benefits that also emerge as by-products from research needed to achieve the major goal and these include:

- new fire safety design tools,
- new technology safety products,
- more economical fire suppression systems,
- ultra-fire-resistant materials,
- tailored fuel properties, and
- advanced fire safety assessment technologies.

Technology transfer of these products to related industries will have positive effects on safety of life and industrial competitiveness in the non-aviation sectors as well.

1 Based on allocated benefit for improvements in fire safety and fuel safety (Appendix A)

# APPENDIX A

# BENEFIT ESTIMATES SUMMARY

This appendix is the executive summary from a report titled "Benefit Estimates of the FAA's Aircraft Safety Research Program, 1992-2001." This report was prepared for the Federal Aviation Administration by Gellman Research Associates, Inc., under subcontract to Galaxy Scientific Corporation.

## EXECUTIVE SUMMARY

This report develops and applies a methodology for estimating the benefits of Federal Aviation Administration (FAA) Aircraft Safety Research Programs. The focus of this report is on the methods used to define a study population of historical aircraft accidents, to apply economic valuation criteria, to assign accidents and their estimated costs to FAA Aircraft Safety Research Programs, and to project the future benefits of these research programs. The primary sources of data are National Transportation Safety Board (NTSB) electronic accident data files.

### ES.1 U.S. AIR CARRIER JET AIRCRAFT ACCIDENTS, 1964 TO 1988

NTSB classifies each accident by four levels of aircraft damage (hull loss, substantial, minor and none) and personal injuries (fatal, substantial, minor, and none) which characterize the accident and its costs. The sources for this report's monetary cost estimates of air carrier accidents are standard FAA values to assign statistical unit costs to aviation injuries, and replacement and restoration costs to damaged aircraft. All valuations in this study are in terms of estimated 1991 dollars.

This report uses data from the 1964 to 1988 time period[1], during which time there are 624 jet aircraft accidents for U. S. air carriers with a total estimated cost of $7.4 billion. This is compromised of personal injury costs (78 percent), aircraft damage (18 percent) and Government investigation cost (4 percent).

*Table ES.1* presents a classification of these accidents and their estimated costs according to NTSB's aircraft damage and injury index classifications. For example, there were 62 accidents characterized by fatal injury and hull loss (10 percent of all accidents in this study) with an estimated cost of $5.9 billion (79 percent of total accident costs).

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[1] More recent data are not available because the NTSB requires a few years to close out the accident record before it is released in machine-readable form.

*Table ES.1. U.S. Air Carrier Jet Aircraft Accidents 1964-1988*

| Injury Index by Aircraft Accident Damage<br>Most Severe Injury Sustained | | | | | |
|---|---|---|---|---|---|
| **Aircraft Damage** | **No Injury** | **Minor Injury** | **Serious Injury** | **Fatal Injury** | **Total** |
| None | 3 | 0 | 259 | 6 | 268 |
| Minor | 10 | 0 | 47 | 0 | 57 |
| Substantial | 139 | 40 | 36 | 4 | 219 |
| Hull Loss | 4 | 1 | 13 | 62 | 80 |
| **Total** | 156 | 41 | 355 | 72 | 624 |

| Estimated Total Accident Cost<br>($91 Million)<br>Most Severe Injury Sustained | | | | | |
|---|---|---|---|---|---|
| **Aircraft Damage** | **No Injury** | **Minor Injury** | **Serious Injury** | **Fatal Injury** | **Total** |
| None | $1.3 | -- | $329.7 | $13.5 | $344.5 |
| Minor | $4.2 | -- | $101.2 | -- | $105.4 |
| Substantial | $310.5 | $86.8 | $162.4 | $231.1 | $790.8 |
| Hull Loss | $49.9 | $6.4 | $242.6 | $5,897.4 | $6,196.3 |
| **Total** | $365.9 | $93.2 | $835.9 | $6,142.0 | $7,437.0 |

## ES.2 APPLICATION OF U.S. AIR CARRIER JET AIRCRAFT ACCIDENTS TO FAA AIRCRAFT SAFETY RESEARCH PROGRAMS

The FAA Aircraft Safety Research Plan designated two general groups of research tasks:

- The first group is centered on preventing new factors created by new or emerging technologies from becoming causes of aircraft accidents prior to or as they are employed in the aircraft fleet (e.g., composite materials, fly-by-wire, and so forth).

- The second group of tasks is directed at reducing the number of aircraft accidents of types that have occurred in the past, or increasing onboard survivability when an aircraft accident occurs.

The later group of tasks is the focus of this report since they are represented in the historical accident record and therefore can be studied to estimate their costs. The former group is directed toward developing new technologies that are minimally represented in the U.S. air carrier jet aircraft fleet.

| | Occurrence Prevention | Impact Mitigation |
|---|---|---|
| Flight Safety Research | | |
| Adverse Flying Conditions | X | |
| Control System safety | X | |
| Aging Aircraft | | |
| Structural Design and Repair | X | |
| Inspection | X | |
| Engine and Fuel Safety | | |
| Engine Structural Safety | X | |
| Engine Reliability | X | |
| Fuel Safety | | X |
| Structural Safety | | |
| Airworthiness | N/A | N/A |
| Crashworthiness | | X |
| Aircraft Systems Fire Safety | | |
| Materials Fire Safety | | X |
| Fire Management | | X |
| Systems | | X |

N/A: Not applicable to historical accident record, but expected to reduce accidents and associated costs in the future.

***Figure ES.1. Assignment of FAA Aircraft Safety Research Programs***

The FAA Aircraft Safety Research Plan is divided into five major program areas and a total of 12 task groups as shown in *Figure ES.1.* Some tasks within a research area have a more generalized purpose and therefore cannot be assigned specific accident cause/factors or impacts. However, understanding of causes of accidents may increase from research in these broader task groups. Other tasks, such as Powerplant Fire Protection, Ground Ice Detection and Removal, Crack Inspection, or Fire Resistant Cabin, are more readily identified with specific accident cause/factors or impacts.

*Figure ES.2* Summarizes the decision criteria used for the application of Aircraft Safety Research Programs to various types of accidents. Once these criteria have been applied, *Figure ES.3* shows the proportions of accidents to which the programs can and cannot be readily applied. Of the 624 accidents in the study population, 192 (31 percent) have cause/factors which correspond to particular Aircraft Safety Research Programs. The cost of these accidents is approximately $5.1 billion, or 69 percent of the total cost of all 624 accidents.

| Decision Criteria for Application of Accidents To FAA Aircraft Safety Research Programs | |
|---|---|
| **Program** | **Assignment Criteria** |
| Flight Safety | — All "Flight Control Systems" Cause/Factors<br>— "Icing Conditions, Deicing"<br>— "Incorrect Flight Control Settings"<br>— Several accidents based on forward looking terrain/obstruction avoidance causes |
| Aging Aircraft | — All "Structural" Cause/Factors<br>— "Flight Control" Cause/Factors removed and added to Flight Safety<br>— Accidents added from narrative review of corrosion as cause<br>— Powerplant accidents with turbine blade failure |
| Engine Safety | — All "Powerplant" Cause/Factors |
| Fuel Safety | — Post-crash fire accidents<br>— In-Flight fire accidents with Powerplant Cause/Factors |
| Structural Safety* (Crashworthiness) | — Airworthiness Program not applicable. Based on advanced materials<br>— All "Hull Loss" accidents that were "Survivable"<br>— Several "Non-Survivable" accidents based on review of crash dynamics similar to "Survivable" accidents (speed, angle, deceleration rate, etc.) |
| Fire Safety | — All Post-Crash Fire accidents<br>— All In-Flight Fire accidents |
| *Subsequent to completion of the research for this study, the Aircraft Safety Research Program added a component to the structural safety program which includes research into landing gear, tires, wheels, and brake systems. | |

***Figure ES.2. U.S. Air Carrier Jet Aircraft Accidents***

## ES.3 ESTIMATED BENEFITS OF AIRCRAFT SAFETY RESEARCH

By calculating the costs of the various accidents to which each research program applies, this study estimates the potential benefits of the Aircraft Safety Research Program elements. Two estimates of the benefits of individual Aircraft Safety Research Programs are presented in this report. The are defined in the following way:

- The *maximum estimate* of benefits represents the total estimated cost of each aircraft accident that can be applied to an individual FAA Aircraft Safety Research Program.
- The *allocated estimate* is calculated by dividing the cost of each accident among all programs which can be applied to that accident. A program's allocated estimate is therefore the sum of such allocations from all accidents.

## Application to FAA Aircraft Safety Research Programs

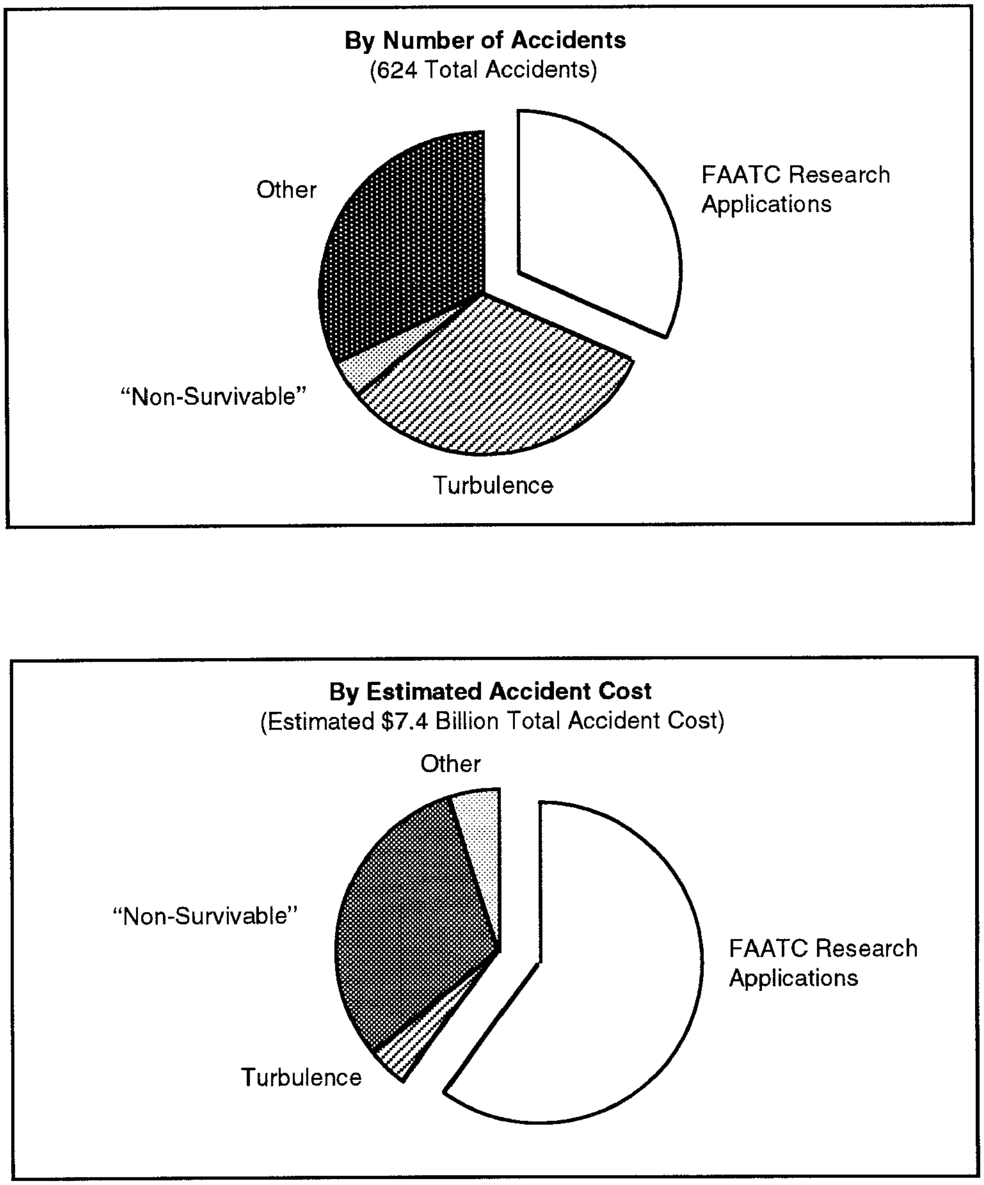


***Figure ES.3. U.S. Air Carrier Jet Aircraft Accidents 1964-1968***

The rationale for calculating two estimates for each research program is as follows. One accident may correspond with more than one program area. Since the application of any one of those programs could have eliminated most or all of the cost of the accident, the entire cost of the accident is added to the maximum benefits estimated for all programs associated with that accident. While the maximum estimate is a good relative measure of the potential cost savings of various program areas, the estimate will overstate the total benefits of FAA Aircraft Safety Research Programs as a whole. The total benefits of FAA Aircraft Safety Research can not exceed the estimated costs of the accidents to which they apply.

For this reason, the allocated estimate overcomes the problem of overstating the benefits from accidents with applications to more than one research program each. By allocating the total estimated costs of a multiple-application accident equally among the potential benefits of all research programs with applications to that accident, the total benefits of all FAA Aircraft Safety Research Programs will be equal to the total costs of the accidents to which the programs apply. This would understate the benefits of individual research programs because an accident might be prevented by success in only one research area.

*Table ES.2* presents a summary of the estimated maximum and allocated benefits from the applications of U.S. air carrier jet aircraft accidents to FAA Aircraft Safety Research Programs.

***Table ES.2. U.S. Air Carrier Jet Aircraft Accidents 1964-1988***

**Summary of Estimated Aircraft Accident Cost Applied to FAA Aircraft Safety Research Programs ($91 Million)**

| FAATC Program | Number of Accidents | Allocated Accident Cost | Allocated Accident Annual Cost | Maximum Accident Cost | Maximum Accident Annual Cost |
|---|---|---|---|---|---|
| PREVENT OCCURRENCE | | | | | |
| Flight Safety | 43 | $491.8 | $19.7 | $1,654.2 | $66.2 |
| Aging Aircraft | 66 | $156.4 | $6.3 | $273.7 | $10.9 |
| Engine Safety | 52 | $150.4 | $6.0 | $444.4 | $17.8 |
| MITIGATE IMPACT | | | | | |
| Fuel Safety | 85 | $1,456.7 | $58.3 | $4,098.7 | $163.9 |
| Crashworthiness | 64 | $1,527.5 | $61.1 | $4,071.1 | $162.8 |
| Fire Safety | 96 | $1,350.3 | $54.0 | $4,007.8 | $160.3 |

For example, the estimated total accident cost (or maximum estimated benefits) for 43 accidents with applications to FAA Aircraft Safety Research is approximately $1.7 billion which is an average of $66.2 million per year. The estimated allocated accident cost is $491 million, which is an average of $19.7 million per year.

*Table ES.3* divides the accidents according to occurrence prevention and impact mitigation. Occurrence prevention tasks apply to 132 of 192 accidents, or 69 percent of the accidents and 39 percent of the estimated accident cost of accidents. Impact mitigation tasks apply to 115 of the 192 accidents, or 60 percent of the accidents and 96 percent of the estimated cost of accidents. There are 57 accidents with applications to both occurrence prevention and impact mitigation tasks. Their estimated cost is

*Table ES.3. U.S. Air Carrier Jet Aircraft Accidents 1964–1988*

| Application to FAATC Aircraft Safety Research Programs Occurrence Prevention and Impact Mitigation | | | | | | |
|---|---|---|---|---|---|---|
| | | | Occurrence Prevention Not Impact Mitigation | | Both Programs | |
| | No. of Accidents | $ Total (Mil) | No. of Accidents | $ Total (Mil) | No. of Accidents | $ Total (Mil) |
| Occurrence | 132 | $1,975.6 | 75 | $157.0 | 57 | $1,818.6 |
| Prevention | Avg.: | $15.0 | Avg.: | $2.09 | Avg.: | $31.9 |
| | | | Impact Mitigation Not Occurrence Prevention | | Both Programs | |
| Impact | 117 | $4,974.6 | 60 | $3,156.0 | 57 | $1,818.6 |
| Mitigation | Avg.: | $42.5 | Avg.: | $52.6 | Avg.: | $31.9 |

approximately $1.8 billion. As a result, the maximum application of occurrence prevention research tasks would reduce the maximum estimated benefits of impact mitigation research from $5.0 billion to $3.2 billion, or a 36 percent reduction.

There are no FAA Aircraft Safety Research Program occurrence prevention task applications for 60 accidents with impact mitigation task applications (51 percent of all impact mitigation accident applications and 64 percent of the estimated accident cost).

## ES.4 PROJECTED BENEFITS OF FAA AIRCRAFT SAFETY RESEARCH, 1992-2001

In order to obtain reasonable estimates of the future benefits associated with the prevention of accidents, a regression model relating the number of accidents per year with exposure (in the form of total hours flown) and time was estimated. Apart from exposure, it is likely that improved safety measures, the introduction of newer aircraft, and other factors may be contributing to a lower accident rate (number of accidents per hours flown) since the mid-1970s. Consequently, a time trend variable has been incorporated to act as a proxy for these effects. As can be seen in *Figure ES 4,* the model yields predictions that conform well with the actual data for most years in the sample period. In addition, projections for future years show a relatively slow rise in the number of annual accidents.

Overall, 196 U.S. air carrier jet aircraft accidents are forecast in this report for the period from 1992 to 2001, of which 61 accidents (31 percent) are estimated to have potential applications to FAA Aircraft Safety Research Programs. The estimated total cost of these accidents is $2.3 billion (an average of $233 million per year) and the estimated benefits of FAA Aircraft Safety Research Programs is approximately $1.6 billion (averaging $160.9 million per year, equal to 69 percent of total accident cost). It must be noted that this does not incorporate benefit estimates for accident types not in the historical record, but which may occur in the future.

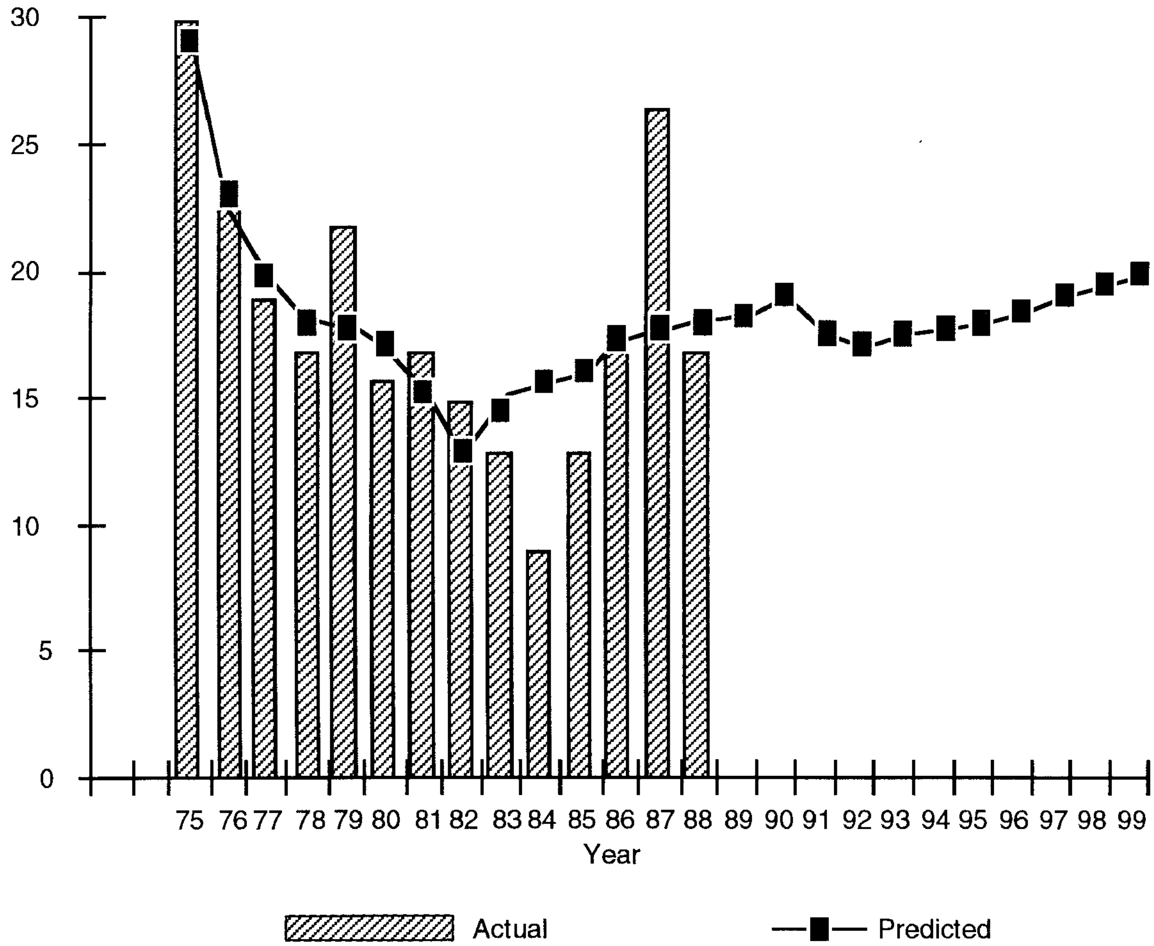


***Figure ES.4. U.S. Air Carrier Jet Aircraft Accidents***

*Table ES.4* presents a summary of the estimated average annual maximum and allocated benefits from the application of FAA Aircraft Safety Research Programs to U.S. air carrier jet accidents for the period 1992-2001. For example, the estimated annual benefits of Flight Safety Research will range between the allocated and maximum estimates of $15.7 million and $52.9 million, respectively. The actual benefits realized will be determined by how effective the individual aircraft safety research programs are in reducing specific types of aircraft accidents or in mitigating their effect. The actual benefits also depend on when research outcomes are available for dissemination and when they become embodied in the U.S. air carrier fleet.

*Table ES.4. . Air Carrier Jet Aircraft Accidents*
*1992–2001*

| **Summary of Projected Annual Benefits for FAA Aircraft Safety Research Programs ($91 Million)** | | |
|---|---|---|
| **FAATC Program** | **Allocated Annual Benefits** | **Maximum Annual Benefits*** |
| **Prevent Occurrence:** | | |
| Flight Safety | $15.7 | $52.9 |
| Aging Aircraft | $5.2 | $8.9 |
| Engine Safety | $4.6 | $13.3 |
| Total Prevent Occurrence | $22.5 | $62.1 |
| **Mitigate Impact:** | | |
| Fuel Safety | $47.0 | $132.4 |
| Crashworthiness Safety | $46.9 | $124.8 |
| Fire Safety | $41.5 | $122.7 |
| Total Mitigate Impact | $135.4 | $156.4 |
| **FAATC Program Total** | **$160.9** | |

* Column does not add because the full costs of some accidents are applied to more than one program.