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Program Plan
Wake Vortex

May 1990

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION
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16. Abstract

This program plan describes the studies and research which will result in an increase in airport capacity without a reduction in safety. Although earlier programs made progress in a number of areas, they were terminated before they could significantly impact operations. Due to the need for increased capacity at airports, and in response to recommendations of an industry task force, the Federal Aviation Administration has revitalized its wake vortex research. These revitalized activities are presented in this Wake Vortex Program Plan.

The Wake Vortex Program Plan will focus on areas wherein existing knowledge is inadequate and wherein the greatest gains may be possible. Six major activities are addressed: (1) review and analysis of wake vortex research; (2) development of new recommended aircraft classification and separation standards; (3) characterization of wake vortices; (4) development of wake vortex warning systems; (5) vortex alleviation and modification; and (6) updating or development of user educational materials and information. A phased approach will be used, with decision points at the completion of each program phase.

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EXECUTIVE SUMMARY

All aircraft produce wake vortices, a pair of "horizontal tornadoes" that may present a hazard to following aircraft, particularly in terminal areas. This phenomenon has been recognized since the beginning of powered flight, but it was not a major concern until the late 1960s, when heavy wide-body jets were introduced. Although the chance of an aircraft encountering a hazardous vortex is very small, it has been necessary to increase aircraft separations -- using conservative estimates of hazard duration -- to give vortices more time to decay and ensure system safety. This protection comes at a high price: the increased separations necessitated by wake vortices reduce airport capacity by an estimated 15 percent.

The demand for airport capacity has steadily increased, resulting in unacceptable delays and higher operating costs. At the same time, vortex-imposed separation standards impede efforts to increase capacity, restricting the system's ability to meet growing demand. Compounding the problem is the number of new large aircraft that have been introduced into the system.

The goal of the Federal Aviation Administration (FAA) Wake Vortex Program is to increase capacity and reduce delays by eliminating vortex restrictions, when meteorological conditions permit, without compromising safety. Although earlier programs made progress in a number of areas, they were terminated before they could significantly impact operations. Due to the need for increased capacity, and in response to recommendations of an industry task force, the FAA has revitalized its wake vortex research. These revitalized activities are presented in this Wake Vortex Program Plan.

PROGRAM OBJECTIVE AND PRODUCTS

The Wake Vortex Program will apply existing knowledge and new technologies to reducing terminal-area separation standards. Through these efforts, the FAA aims to increase airport capacity by 12 to 15 percent, while maintaining or even improving system safety. The program will yield both near- and far-term payoffs, with some improvements completed over the next few years. Products that will bring immediate capacity gains include the following:

- Recommended changes to aircraft classifications and separation standards that allow more efficient use of the airspace --
  - Heavy/Heavy separations.
  - Small and Large behind Heavy separations.
  - Fixed-wing/rotorcraft separations.
  - Aircraft classification scheme using more than three vortex classes (potentially suitable for use in automated controller spacing aids).
- Report characterizing wake vortices of new-generation aircraft.
- Operational doctrine and requirements for wake vortex warning systems.
- Several new or upgraded vortex-measuring systems.

- Analysis of airport capacity gains.
- Feasibility study on airborne wake vortex sensing and warning.
- Analysis of T-tail aircraft hazards.
- Analysis of meteorological-data requirements for reducing separation standards under a variety of conditions.
- Resumption of National Aeronautics and Space Administration (NASA) efforts, including vortex modeling, vortex alleviation, and airborne-sensor investigations.

These initial products are part of a more expansive, long-term research and development program. Ultimately, the FAA plans to develop a wake vortex warning system that will reduce interarrival aircraft separations and to issue a revised set of aircraft classifications and separation standards. Program activities will build on previous efforts, making full use of existing data and technology when they are applicable.

PREVIOUS ACTIVITIES

Research conducted by the FAA and NASA during the 1970s addressed several approaches to eliminating the vortex problem. FAA efforts emphasized the collection of data on vortex behavior and the development of a wake vortex warning system. NASA research concentrated on vortex modeling and vortex alleviation at the source.

To improve knowledge of vortex behavior, the FAA developed and installed sensors to detect and track vortices near the ground. Analysis of sensor data revealed that because the conditions leading to a hazardous vortex encounter are rare, the separations imposed on aircraft are often too conservative. By compressing separations when vortices do not pose a threat, it was concluded, much of this lost capacity could be regained.

In the mid-1970s, the FAA developed a Vortex Advisory System (VAS) that determined when separations between landing aircraft could be safely reduced. Using measurements of ambient winds, this system indicated to controllers when vortices had either moved away from the approach path of the following aircraft or dissipated to a safe level. Although a prototype was installed at Chicago's O'Hare International Airport, procedural problems prevented its deployment. Among these difficulties were the use of the system under visual flight rules and the "go/no go" character of its advisories.

At NASA, complementary research addressed vortex modeling and alleviation. Considerable progress was made in modeling the generation of vortices and the mechanics of vortex transport and decay. NASA also investigated aircraft design changes that would eliminate or reduce the strength of wake vortices.

During the 1980s, fiscal constraints and a temporary decline in demand led to the cancellation of many of these programs. As demand has grown, however, the need for increased capacity has become recognized, as has the need for a revitalized Wake Vortex Program.

WAKE VORTEX PROGRAM ACTIVITIES

The Wake Vortex Program focuses on areas wherein existing knowledge is inadequate and wherein the greatest gains may be possible. Six major activities are addressed: (1) review and analysis of wake vortex research; (2) development of new recommended aircraft classifications and separation standards; (3) characterization of wake vortices; (4) development of wake vortex warning systems; (5) vortex alleviation and modification; and (6) updating or development of user educational materials and information. A phased systems approach will be used, with decision points at the completion of each program phase.

Review and Analysis

Work will expand the FAA's knowledge about wake vortices and quantify the benefits of ameliorating vortex hazards. All previous and current research will be evaluated, with documentation completed as necessary. To the greatest extent possible, the FAA will use existing data to develop a new set of aircraft separation criteria. Moreover, a capacity analysis will determine the actual gains to be brought about by eliminating vortex hazards. If gains are significant, the FAA will use results of the analysis for program planning and prioritization.

Aircraft Classifications and Separation Standards

A major program element is the development of new aircraft classifications, leading to more efficient separation standards. Under the current scheme, which considers only the maximum certificated gross takeoff weight, aircraft are divided into three classes for wake vortex purposes: Small, Large, and Heavy. The FAA will reexamine the rationale for defining these classes, and the resulting separation standards, and determine their efficacy. Vortex hazard and classification models will aid in developing new recommended separation criteria, based on new proposed aircraft classes. The FAA also will analyze the vortex characteristics of new-generation aircraft to determine where these aircraft fit in the new (or existing) classification scheme. Before implementing new classifications and standards, the FAA will test them in both a simulated and an operational environment.

Initially, the FAA will focus on a number of specific areas for improvement, in particular the Heavy/Heavy separation, the final-approach separation for Small and Large aircraft following a Heavy, and the use of more than three aircraft classes. In addition to developing a complete set of revised separation standards, later work will assess the validity of parallel-runway separation requirements and will develop rotorcraft separation criteria.

Wake Vortex Characterization

In support of other program activities, the FAA and NASA will further characterize wake vortex behavior through measurement and modeling.

The FAA will acquire preliminary vortex data at a test site using the tower fly-by technique. Additional data will be collected at an airport during normal landings and takeoffs, using three types of upgraded instrumentation: the Laser Doppler Velocimeter, the Monostatic Acoustic Vortex Sensing System, and the Ground Wind Vortex Sensing System. The possibility of obtaining wind and temperature data from other sources, such as the landing aircraft, Terminal Doppler Weather Radar, or other techniques, will also be explored.

In a related activity, NASA will investigate improved modeling of vortex encounters. Models will be incorporated into simulations used to evaluate wake vortex warning systems and new separation standards. Pilot reactions to vortex encounters will be evaluated using aircraft simulators. NASA also will update its models of vortex generation and decay.

Wake Vortex Warning Systems

Warning-system research will concentrate on two areas: development and demonstration of a ground-based system, and investigation of airborne sensors.

The FAA will explore possibilities for a ground-based wake vortex warning system, with the goal of overcoming the operational limitations of the earlier VAS. System development will comprise a series of steps. Initially, the FAA will establish an operational doctrine and requirements for a ground-based system. Depending on these requirements, a system concept will be developed incorporating a dual capability: wake vortex detection and meteorological prediction. After evaluating the system concept, the FAA will develop, install, and test a prototype at an operational airport; assessment of the prototype will gauge both capacity gains and user reactions. If the system is operationally acceptable, a specification will be prepared for implementation.

NASA will investigate new concepts for airborne wake vortex sensing. An early product of this research will be a report on the overall feasibility of airborne detection and avoidance.

Wake Vortex Alleviation and Modification

By modifying aircraft to reduce the strength or duration of wake vortices, hazards could be mitigated and separation standards reduced. NASA is resuming research in this area, in cooperation with the industry, under the Wake Vortex Program.

User Education

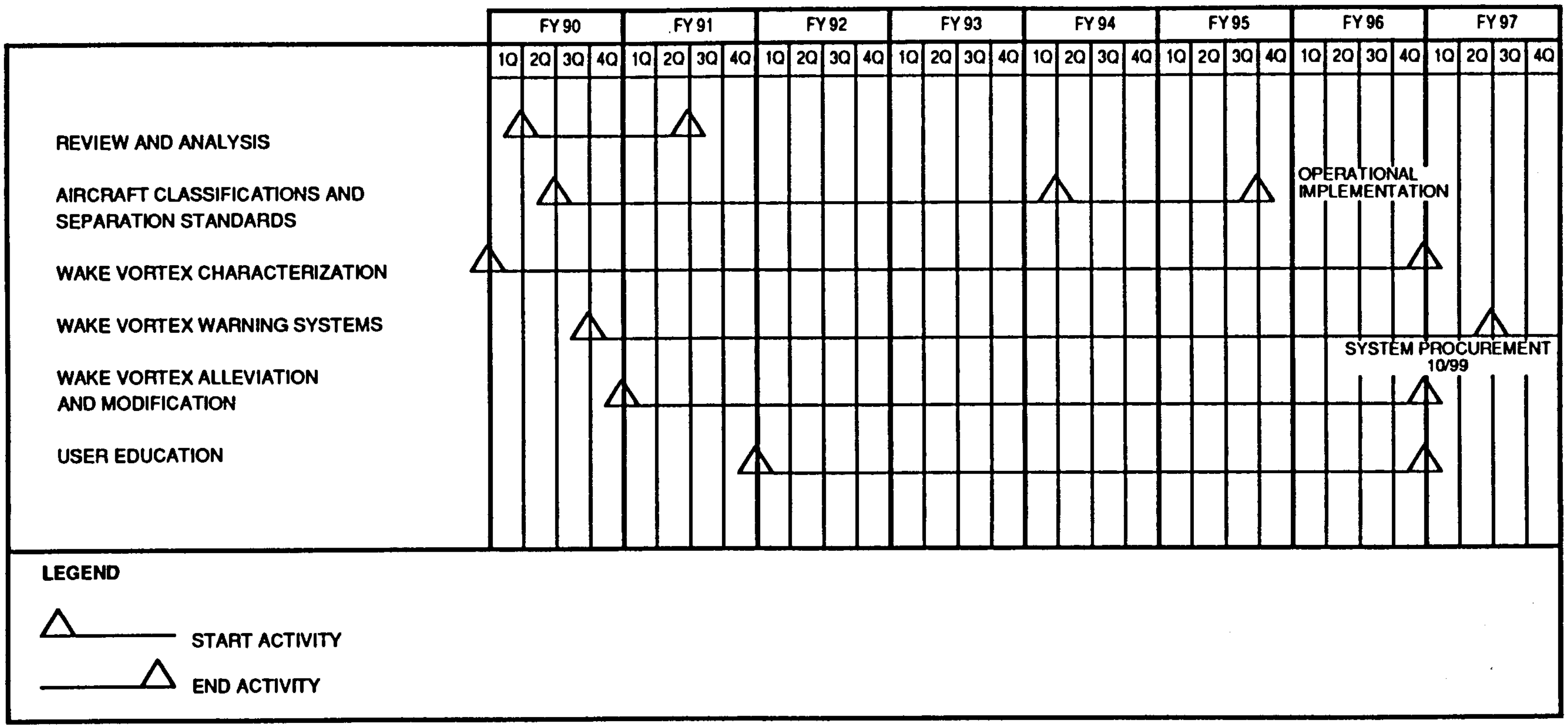
As program products are introduced into the air traffic control system, the FAA will develop or update pilot advisories and training materials. New educational aids will alert pilots to vortex dangers and provide information on hazard avoidance.

PROGRAM MANAGEMENT

The Wake Vortex Program is managed by the FAA Technical Center, Airport Technology Branch (ACD-110). Program activities are conducted by several organizations, including NASA, the Transportation Systems Center, and the National Oceanic and Atmospheric Administration. The advice of a working group and technical advisory committee will be an integral part of the program.

SCHEDULE AND DECISION POINTS

The figure below illustrates the schedule for major program activities. For decision points and intermediate milestones, see the detailed schedule in Section 7 of the program plan.



WAKE VORTEX PROGRAM SCHEDULE

FUNDING

The estimated funding needed to accomplish program objectives over the next 7 years is as follows:

WAKE VORTEX PROGRAM FUNDING ($M)

	FY 90	FY 91	FY 92	FY 93	FY 94	FY 95	FY 96
FAA	2.6*	2.1*	5.5	5.4	4.8	4.7	4.3
NASA	--	--	3.0	3.5	4.5	4.5	3.5
TOTALS	2.6	2.1	8.5	8.9	9.3	9.2	7.8

* Includes FAA funding for NASA activities.

1. INTRODUCTION

The growth of commercial aviation has demanded that the nation's airports safely and efficiently accommodate increasing levels of traffic. At the same time, environmental, economic, and other constraints have not allowed airports to increase capacity to meet demand. Coupled with growing traffic, these constraints have contributed to flight delays and to delay-related fuel consumption.

Because aviation demand is not being met with new airports or runways, the Federal Aviation Administration (FAA) is increasing capacity by modernizing the air traffic control (ATC) system. But although technology exists to improve capacity, restrictions imposed because of wake vortices tend to cancel out some of the benefits of ATC system improvements: Vortex-imposed separation standards present an obstacle to increased capacity, and may substantially limit the future growth of air transportation.

1.1 THE WAKE VORTEX PHENOMENON

All aircraft generate wake vortices, a pair of counter-rotating air masses created by the wing as an aircraft produces lift. Under the right conditions, these vortices may present a hazard to following aircraft, especially in terminal areas. The wake vortex problem is complex, due to the number of variables involved; for example, although a vortex is initially characterized by the generating aircraft (weight, wingspan, speed, flap and spoiler settings, lift distribution), the encounter itself (safe or hazardous) is characterized by the trailing aircraft (speed, wingspan, roll-control capability, phase of flight). Moreover, atmospheric conditions such as crosswind, turbulence, and shear play a leading role in determining just how long a vortex remains hazardous.

Although the wake vortex phenomenon has been recognized since the beginning of powered flight, it was not a major concern until the late 1960s, when heavy wide-bodied jets were introduced. Before 1970, separation standards were based on radar operating limits and, to a lesser extent, on runway occupancy restrictions; there were no aircraft separations imposed because of wake vortices. With the introduction of wide-body jets, the vortex-hazard potential increased significantly. Accordingly, in 1969 the FAA conducted flight tests to determine the vortex characteristics of jet aircraft. Based on these tests, the agency divided aircraft into three classes for wake vortex purposes, according to the maximum certificated gross takeoff weight: Small (12,500 pounds or less); Large (12,500 to 300,000 pounds); and Heavy (300,000 pounds or more). Classifications were used to establish new aircraft separation standards.

Current separation criteria reflect the original flight tests, with some modifications made in 1975. (Because airport tests indicated that Small following aircraft may require greater separation upon landing, the FAA increased spacings for this aircraft category. Separations for Large and Heavy aircraft were found to be adequate.) Although these conservative aircraft separations effectively preclude the chance of a hazardous vortex encounter, they contribute to capacity problems at many high-traffic airports.

1.2 THE WAKE VORTEX PROGRAM PLAN

The FAA's Wake Vortex Program Plan presents those activities designed to increase capacity by determining when wake vortex restrictions may be relaxed. Section 2 of the plan is an overview of earlier research and development. Section 3 presents the FAA's objective for its revitalized Wake Vortex Program and the phased approach to achieving this objective. The current program is summarized in Section 4, which is organized into six major activity areas. Section 5 addresses the integration of the program's products into the future ATC system. Section 6 describes mechanisms for industry participation in the program and for program oversight. Program schedules are illustrated in Section 7, and Section 8 outlines projected funding requirements. Appendix A is an overview of current scientific knowledge of wake vortex behavior.

2. PREVIOUS ACTIVITIES

Over the past 25 years, research conducted by the FAA and the National Aeronautics and Space Administration (NASA) addressed a number of approaches to eliminating the vortex problem. FAA efforts emphasized the collection of data on vortex behavior and the development of a system to reduce interarrival aircraft separations. NASA activities focused on vortex modeling and on vortex alleviation at the source.

To improve knowledge of vortex behavior, early FAA programs developed sensors capable of detecting and tracking vortices near the ground. (The ground region was emphasized because most vortex-related accidents occur during final approach.) In 1973, several of these systems were installed at New York's JFK International Airport to measure the vortices from landing aircraft; additional sensors were tested as they were developed, and the site was closed in 1977. The FAA established other data-collection sites at Denver (1973), at London Heathrow (1974 to 1975), and at Chicago O'Hare (1976 to 1980). Data on the vortices shed by departing aircraft were collected at Toronto (1976 to 1977) and at Chicago (1979 to 1980).

The FAA data revealed that because the conditions leading to a hazardous vortex encounter are rare, the separations imposed on landing aircraft are often too conservative. It was concluded that much of this lost capacity could be regained by compressing separations when vortices do not pose a threat. In the mid-1970s, the agency developed a Vortex Advisory System (VAS) that determined when separations between landing aircraft could be safely reduced. The VAS used measurements of the ambient winds in the middle-marker region to indicate to controllers when vortices had either moved away from the approach path of a following aircraft or dissipated to an innocuous level. The wind criterion of the VAS algorithm was an ellipse with a major semi-axis of 12.5 knots head (or tail) wind and a minor semi-axis of 5.5 knots crosswind. Wind speeds outside of the ellipse permitted reduced separations.

A VAS prototype was installed at Chicago in 1977, but operational problems prevented its deployment. One difficulty was the use of the system under visual flight rules (VFR). (During visual approaches, pilots have greater freedom to avoid wake vortices by landing long or flying above the glide path; the problem was determining what should be done in VFR when the wind was within the VAS ellipse.) Another problem was convincing pilots that separations could indeed be safely reduced when the wind speed was outside of the ellipse. Finally, air traffic controllers objected to the "go/no go" character of the VAS advisory, signified by changing green and red lights.

At NASA, complementary research addressed wake vortex modeling and alleviation. Substantial progress was made in modeling the generation of vortices and the mechanics of their transport and decay. NASA also investigated aircraft design changes that would eliminate or mitigate the strength of wake vortices -- and thereby reduce chances for a hazardous encounter.

In the 1980s, many of these FAA and NASA programs were cancelled due to fiscal constraints and a temporary decline in demand. (Some work was resumed in 1984 on rotorcraft wake vortices.) Although efforts yielded invaluable information on vortex behavior, much remains to be learned. (See Appendix A for a synopsis of current scientific knowledge.) Before new separation standards can be established, data must be collected on vortex transport and decay, as they are statistical processes; that is, they are the varying products of aircraft characteristics and changing atmospheric conditions. Moreover, the vortex characteristics of various new aircraft types must be examined. Specific areas requiring new research and development are:

- Vortex strength and decay -- Earlier efforts established how vortices move near the ground, but only limited data were collected on vortex decay. Understanding this phenomenon will require new, more complete meteorological data.
- Vortex motion -- To develop standards for parallel and intersecting runways, vortex motion over long distances must be examined.
- Vortex descent -- In the final-approach segment (outer to middle marker), vortex descent is the primary factor precluding an encounter. Data must be collected under various meteorological conditions to assure safety in this segment during periods when separations might be reduced.

3. PROGRAM OBJECTIVE AND APPROACH

To meet the need for increased capacity, the FAA is revitalizing its wake vortex research, focusing on areas wherein existing knowledge is inadequate and wherein the greatest gains may be possible. The revitalized Wake Vortex Program will apply existing data and new technology to reducing terminal-area separation standards. Program activities have one primary objective: increase airport capacity by 12 to 15 percent, while maintaining or even improving system safety. The FAA is employing an integrated systems approach to achieving this objective, composed of five interrelated program phases:

- *Phase 1 -- Planning*. In this phase, now completed, the FAA developed the Wake Vortex Program Plan and coordinated an industry review to ensure that the plan reflects the needs of the aviation community. The plan will be updated as needed to meet changing requirements.
- *Phase 2 -- Review/Analysis/Instrumentation Development.* The agency is reviewing all past and current research and determining the existing level of knowledge; this is necessary to avoid duplicating efforts or overlooking any issues that had an adverse impact on the earlier program. The FAA also will analyze the benefits of mitigating

vortex hazards and, based on this analysis, will decide whether to proceed with specific program activities. The agency will assemble instrumentation that will measure vortex characteristics under varying meteorological conditions, particularly those of new-generation aircraft. Causal factors of vortex transport and decay will be further identified. Knowledge acquired in Phase 2 will be applied in subsequent program phases.

- *Phase 3 -- System Requirements Definition/Recommended Standards Development/Aircraft Classification Development.* In Phase 3, the FAA will define operational requirements for ground-based and airborne wake vortex warning systems. Moreover, the agency will evaluate current separation criteria and, if appropriate, produce a revised set of standards. New recommended aircraft classifications also will be developed during this phase. After simulation and testing, the FAA will decide whether to proceed with requirements or recommendations.
- *Phase 4 -- System Development, Test, Evaluation/Evaluate Recommended Standards/Evaluate Recommended Aircraft Classes.* Using the knowledge acquired in previous phases, the FAA will develop a concept and prototype for a ground-based wake vortex warning system. Following the simulation, testing, and evaluation of this system, the agency will determine if it should be developed and subsequently produced. NASA will investigate airborne wake vortex sensing. Also during this phase, the FAA will test candidate aircraft classifications and separation standards in both a simulated and an operational environment.
- *Phase 5 -- Issue System Specification/Standards/Aircraft Classes.* The agency will submit warning-system specifications, separation standards, and aircraft classifications to the appropriate FAA office. This will occur only after prior phases have been completed and after all concerned have agreed on the system design or the recommended standards. The final activity will be the implementation of the warning system and new separation criteria.

Program phases and primary activities are depicted in Figure 1. As indicated, all efforts support one of three major products: wake vortex warning systems, new recommended separation standards, or new aircraft classifications. The progress of each "path" is independent of the others, although some activities are interrelated. After completing a program phase, the FAA will decide if the expected benefits of an activity justify its costs; work will proceed to the next phase only if capacity gains are shown to be significant.

4. WAKE VORTEX PROGRAM ACTIVITIES

The Wake Vortex Program represents a balanced approach to increasing airport capacity. Activities will build on previous efforts, making full use of existing data and technology when they are applicable. Six major areas are addressed: (1) review and analysis of wake vortex research; (2) development of new recommended aircraft classifications and separation standards; (3) characterization of wake vortices; (4) development of wake vortex warning systems; (5) vortex alleviation and modification; and (6) updating or development of user educational materials and information.

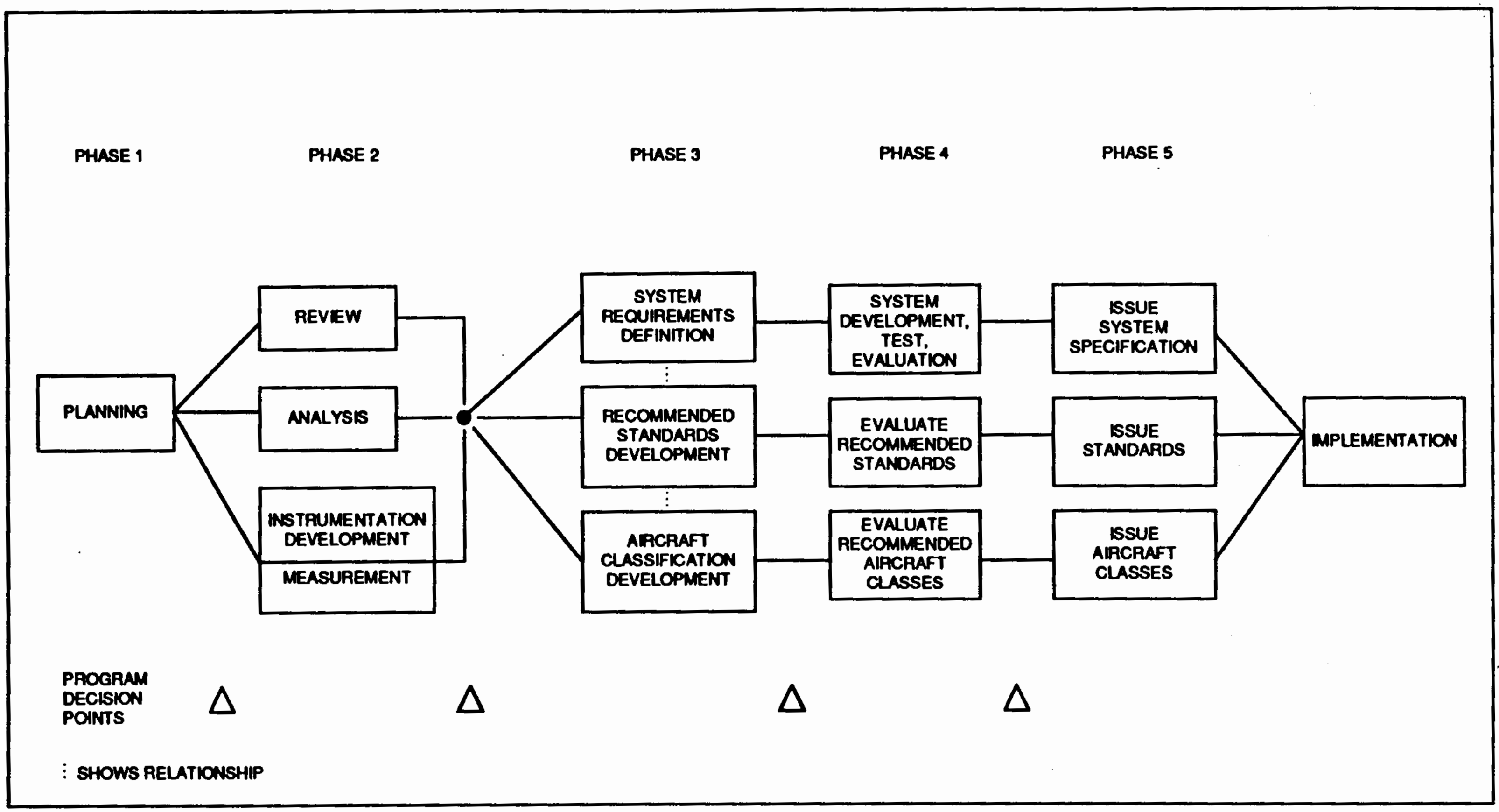


FIGURE 1. WAKE VORTEX PROGRAM FLOW

4.1 REVIEW AND ANALYSIS

The FAA is establishing the direction and emphasis of the Wake Vortex Program through a research review and an analysis of potential capacity gains.

4.1.1 Review of Wake Vortex Research

The FAA is reviewing all previous wake vortex research and will complete documentation as necessary. To the greatest extent possible, existing data will be used to develop and evaluate a new set of aircraft separation criteria. The agency also will evaluate current research, such as the wake vortex tests conducted by the Federal Republic of Germany. Following its review of wake vortex activities, the FAA will issue reports summarizing current knowledge and identifying areas for further study.

4.1.2 Airport Capacity Analysis

A capacity analysis will determine the actual benefits of mitigating vortex hazards. The study will consider various runway configurations at high-traffic airports (single, parallel, converging, and crossing) and will address both arrivals and departures. If capacity gains are significant, the FAA will apply results of the analysis to program planning and prioritization. A report will follow the completion of this effort.

4.2 AIRCRAFT CLASSIFICATIONS AND SEPARATION STANDARDS

A major goal of the Wake Vortex Program is to establish new aircraft classifications and separation standards that maximize airport capacity. Initial efforts will focus on a number of specific improvement areas, in particular the Heavy/Heavy separation, the final-approach separation for Small and Large aircraft following a Heavy, and the use of more than three aircraft classes. Ultimately, the FAA will issue a revised set of classifications and separation criteria for three types of airport operations: single runway, parallel and intersecting runway, and rotorcraft.

4.2.1 Single-Runway Operations

Through flight tests, the FAA will establish revised aircraft classifications as a basis for more efficient separation standards. The vortex characteristics of T-tail aircraft will also be examined.

4.2.1.1 Aircraft Classification

As discussed in Section 1, aircraft are now divided into three weight classes for wake vortex purposes: Small, Large, and Heavy. The range for Large aircraft (12,500 to 300,000 pounds) is particularly broad. The FAA will investigate the possibility of dividing aircraft into more than three weight classes or of establishing new classes. Efforts will address both reclassification of older aircraft and classification of new-generation aircraft.

4.2.1.1.1 Reclassification of Aircraft -- The FAA will explore the feasibility of reclassifying aircraft to include factors other than weight that have a direct bearing on separation standards; for instance, by considering the actual weight of a landing aircraft (which is less than the certificated gross takeoff weight), that aircraft might be reclassified and the separation standard reduced. Similarly, the number, thrust level, and location of engines on the lead aircraft may all influence the strength of vortices at the downstream location of the encountering aircraft. Reexamination of aircraft classifications will include the following:

- The FAA will analyze tests conducted in the 1970s and, if applicable, use data to develop new classifications and separation standards. Current research will also be considered.
- A simulation for evaluating candidate standards will be developed at the FAA Technical Center. It will enable the FAA to assess both the standards' effectiveness and controllers' abilities to handle new (or more) aircraft classes.
- New separation standards will be tested at a major airport. Tests will verify standards and determine if they are operationally acceptable. Data also will support development of operational simulations.

Program efforts will yield an operationally feasible set of classifications and separation standards and a plan for their incorporation into the ATC system. The FAA will decide whether to proceed with specific candidate standards following the simulated and operational evaluations (see Figure 1).

4.2.1.1.2 Classification of New-Generation Aircraft -- Tests have shown that similarly sized aircraft can have significant variations in wake vortex duration; thus, in the absence of validated predictive methods, vortex data are needed to determine where new aircraft (such as the 757/767 and the A-300) fit in any new classification scheme. The program for new-generation aircraft will comprise the following activities:

- An instrumented tower (see Section 4.3.1.1.1) will be upgraded and used to measure vortex characteristics. Located in Idaho Falls, Idaho, the facility is operated by the National Oceanic and Atmospheric Administration (NOAA). Aircraft manufacturers and airlines will be asked to bring new aircraft to the test site for tower fly-bys so that vortex-generating characteristics may be measured. Aircraft will be tested in landing, takeoff, and other configurations. A series of reports will document test results.
- After tower fly-bys, an airport test site will provide vortex-strength data for different aircraft under the same meteorological conditions. Enough cases will be considered to ensure statistical confidence. Based on these tests, a report will further characterize new-aircraft wake vortices.

Upon completing all tests, the FAA will issue a final report documenting new-aircraft vortex characteristics and recommending associated classifications and separation standards.

4.2.1.2 *T-Tail Aircraft Studies*

The vortices of T-tail aircraft, such as the B-727 and DC-9, are thought to be relatively long-lasting and strong enough to present a hazard to Small following aircraft. The FAA will address this issue by reviewing prior research and, if necessary, by collecting additional data at the NOAA test site. If a problem indeed exists, the FAA will determine the strength, duration, and characteristics of the T-tail vortices. A report will be published at the conclusion of these studies.

4.2.2 Parallel- and Intersecting-Runway Operations

At many airports, landings and takeoffs are conducted on closely spaced parallel or converging runways. With parallel runways, vortices from the upwind runway can, under the right wind conditions, reach the other with enough strength to constitute a hazard. For this reason, the FAA requires a separation of at least 4,300 feet between parallel runways for simultaneous independent instrument flight rules operations, and a 2,500-foot separation under VFR. A similar problem exists for takeoffs and landings on intersecting runways; these operations are even more complex, since the vortex hazard depends on the specific runway configuration and type of operation.

Earlier research showed that vortices move between runways in ground effect, often traveling 1,700 feet from their point of generation; however, because of sensor limitations, the FAA did not measure how much farther the vortices traveled or their actual strength. New research will close this knowledge gap, with the aim of increasing the capacity of parallel and intersecting runways. "Long-line" sensors located out to 2,500 feet will measure vortex strength and motion under all conditions. Data will allow the agency to characterize vortex motion in ground effect, as well as its dependence on factors such as the generating aircraft, meteorological parameters, and terrain.

After concluding testing and analysis, the FAA will recommend new separation standards for parallel and converging runways. Knowledge will ultimately support the automation of these types of airport operations.

4.2.3 Rotorcraft Operations

Though similar to those of fixed-wing aircraft, the vortices shed by heavy, slow-moving rotorcraft may be especially strong, if not long-lasting. One FAA plan to increase capacity involves greater use of rotorcraft, necessitating development of special classifications and separation standards. Activities in this area will be conducted under the FAA's Rotorcraft Separation Standards effort and applied to the Wake Vortex Program as needed. Specific efforts include the following:

- Rotorcraft test data collected in the 1980s will be reviewed and documentation completed. Data include both vortex-generation and vortex-encounter cases.
- Additional data will be collected as needed. In particular, new testing will address rotorcraft penetrations of vortices shed by rotorcraft and by fixed-wing aircraft.
- Data on tiltrotor wake vortices will be collected as soon as these aircraft are available.

Using rotorcraft data, the FAA will develop a candidate set of classifications and separation standards. Criteria will address rotorcraft/rotorcraft, rotorcraft/fixed-wing, and fixed-wing/rotorcraft separation requirements.

4.3 WAKE VORTEX CHARACTERIZATION

All Wake Vortex Program activities rely on accurate characterizations of vortex behavior. These characterizations must allow the prediction of vortex movement and strength under constantly changing meteorological conditions, for a wide variety of generating aircraft. Two related efforts address this program requirement: wake vortex measurement and vortex modeling.

4.3.1 Wake Vortex Measurement

The FAA will collect data at test sites after developing or upgrading vortex-measuring instruments. Data will be used to validate NASA's wake vortex models (see Section 4.3.2).

4.3.1.1 Data-Collection Sites

Although much was learned about vortex behavior in the 1970s, additional measurements are needed to meet current requirements. The FAA will acquire data at two test sites in support of aircraft reclassification and other efforts. The first, the NOAA site at Idaho Falls, will be used for tower fly-by tests; the other will be a high-capacity airport where instrumentation may be deployed for long-term data collection. After analyzing measurements, the FAA will issue a wake vortex characterization report.

4.3.1.1.1 NOAA Test Site -- In tower fly-by tests, an aircraft is flown perpendicular to the ambient wind, upwind of the instrumented tower, at predetermined airspeeds, configurations, altitudes, and lateral offsets. Enough data are collected to analyze vortex behavior as a function of various factors, including aircraft configuration and atmospheric conditions.

Under the current program, NOAA will upgrade its tower with improved meteorological instrumentation. The upgraded tower will be used for two purposes: to measure vortex characteristics of test aircraft, especially new-generation aircraft; and to validate instruments such as the Laser Doppler Velocimeter (LDV) and the Monostatic Acoustic Vortex Sensing System (MAVSS), described below. In addition to tower fly-by testing, the FAA and NOAA will conduct wake vortex penetration tests at altitude to determine following-aircraft responses to vortex encounters. The test site will also help validate Doppler radars and other new equipment for possible use with wake vortex warning systems (see Section 4.4.1).

4.3.1.1.2 Data-Collection Airport -- The FAA is considering several airports for a long-term test program. Critical factors in this selection are: (1) the support of the airport operator; (2) the availability of a large, secure area for deployment of vortex instruments; and (3) a mix of air traffic that includes various-sized and new-generation aircraft. At the airport, the FAA will collect vortex data during normal landings and takeoffs, using the upgraded LDV, MAVSS, and Ground Wind Vortex Sensing System (GWVSS).

4.3.1.1.3 Other Test Sites -- Additional sites may be employed on a short-term basis to meet program requirements. Sites may be selected because of their unique vortex problems or used to collect specific data on vortex behavior.

4.3.1.2 Instrumentation

The FAA will update wake vortex sensors to improve their sensitivity and measurement capabilities. Instruments will be upgraded in stages, as funding permits. Of the many sensors tested by the FAA, the LDV, MAVSS, and GWVSS are the most useful for measuring vortices. Additional sensors may be developed to measure meteorological conditions or specific vortex characteristics.

4.3.1.2.1 Laser Doppler Velocimeter -- The LDV was used extensively in the 1970s and was most recently employed to study rotorcraft wakes. To meet the needs of the current Wake Vortex Program, the FAA is upgrading LDV tracking and processing capabilities in stages. Improvements will permit shorter data turnaround times, increased accuracy, and automated vortex tracking, as well as measures of the sign of vortex velocity. The upgraded sensor will help determine the strength, size, and duration of wake vortices for new-generation aircraft and possibly for rotorcraft. Flexible and mobile, it will allow vortex-data collection at any major airport.

4.3.1.2.2 Monostatic Acoustic Vortex Sensing System -- This system comprises several acoustic antennas placed along a line perpendicular to the extended runway centerline. Because it measures the strength of vortices moving laterally in ground effect, the MAVSS has been used to study vortex motion and decay. Developed under the Wake Vortex Program, an improved MAVSS will track slowly moving or stalled vortices and offer automatic, around-the-clock data collection; a long-line version will measure vortex lateral transport. Data from the upgraded MAVSS will be essential for developing a wake vortex warning system.

4.3.1.2.3 Ground Wind Vortex Sensing System -- The GWVSS is an array of single-axis anemometers located on a baseline perpendicular to the flight path of the landing runway. The system's success in tracking wake vortices results from the induced motion of a vortex pair: after generation, vortices descend to the ground, where they separate and level off at a height equal to about one-half of their initial spacing. The GWVSS detects wake vortices by measuring these ground-level winds.

The FAA will improve the GWVSS by automating data collection and adding three-axis anemometers and will install it at the data-collection airport. Although the system's detection threshold for vortices at their equilibrium height appears to be well below the hazard level, the FAA will study a promising technique for extracting vortex-strength information from GWVSS measurements. Such a technique would greatly extend the usefulness of the existing GWVSS database.

4.3.1.2.4 Meteorological Instrumentation -- If wake vortex data are to be accurately interpreted, local weather conditions must be measured and be time-correlated with vortex data. Especially important are measures of temperature and wind profiles to altitudes of 1,000 feet in the area of vortex measurements; information on turbulence or other factors may also be required. The FAA will investigate the possibility of obtaining wind and temperature data from such sources as the landing aircraft and the Terminal Doppler Weather Radar (TDWR). New weather-sensing technologies will also be explored.

4.3.1.2.5 Other Wake Vortex Instrumentation -- In addition to the LDV, MAVSS, and GWVSS, other instruments will be investigated as they become available. The FAA currently is considering new uses of older technologies, such as FM/CW radar and bistatic radar, and newer technologies such as pulsed lasers.

4.3.2 Vortex Modeling

Wake vortex models, developed by NASA, provide theoretical representations of vortex behavior. These models are validated using the FAA's actual vortex measurements. Wake vortex modeling contributes to three major program efforts: development of aircraft classifications and separation standards, development of wake vortex warning systems, and vortex alleviation.

NASA has made considerable progress over the past 25 years in modeling vortex behavior. But although much work has been performed on vortex generation and decay, little has been undertaken on vortex encounters, an important area for both aircraft reclassification and warning-system development. NASA will study the hazards of vortex encounters in cooperation with the FAA. Hazard modeling will address such questions as the following:

- What happens when an aircraft encounters a wake vortex? How do various types of control endeavors affect the resulting motions?
- What control actions should an aircraft take?
- How do the characteristics of an aircraft affect its ability to react to vortex encounters?
- When is a vortex no longer a hazard to an encountering aircraft?

Hazard models will be incorporated into ATC simulations used to evaluate wake vortex warning systems and new separation standards. Pilot reactions to vortex encounters will be examined using aircraft simulators.

In addition to encounter modeling, NASA will update its models of vortex generation and decay; wind-tunnel testing will support this effort. Atmospheric factors, such as turbulence and winds, will be modeled and analyzed.

4.4 WAKE VORTEX WARNING SYSTEMS

Warning-system research will concentrate on two areas: development and demonstration of a ground-based system, and investigation of airborne sensors.

4.4.1 Ground-Based Vortex Warning System

Incorporating active vortex detection and tracking, a ground-based system will give controllers wake vortex warnings for landing and departing aircraft. A goal of the Wake Vortex Program is to develop a ground-based system that overcomes the operational difficulties of the earlier VAS. Such a system will detect vortex hazards and predict when aircraft separations may be reduced. Moreover, it will effectively increase airport capacity by allowing controllers to safely reduce separations whenever vortices do not present a hazard.

Development of a ground-based warning system will proceed in stages:

4.4.1.1 Operational Requirements Development

To produce benefits, a ground-based vortex warning system must be completely integrated into the ATC environment; for example, the system must have a predictive capability of from 15 to 30 minutes to ensure no disruptions in traffic. As an initial step, the FAA will define the system's operational requirements and related ATC procedures. Advice on system requirements and design will be sought from controllers, pilots, airport operators, and air carriers.

4.4.1.2 Concept Development

Based on operational needs, a system concept will be developed incorporating a dual capability: wake vortex detection and meteorological prediction. The system will alert controllers, well in advance, whenever atmospheric conditions make a hazardous vortex encounter possible; as long as there is no hazard, aircraft spacings may be reduced. Should atmospheric conditions change unexpectedly, a sensor will detect vortices stalled in the landing corridor. The warning-system concept must meet two technical requirements:

- Concurrent measures must be taken of vortex behavior and meteorological conditions such as turbulence and winds aloft. The final operational system may incorporate data from the Low-Level Windshear Alert System or the TDWR, meteorological data downlinked from aircraft, data from turbulence sensors, or information from other sources as they become available.
- Operational procedures must be acceptable to ATC personnel: aircraft spacings cannot change frequently. The warning system must predict weather 15 to 30 minutes in advance to permit timely, efficient changes in aircraft spacings. With such notice, controller workload would not be significantly increased, and aircraft already on approach would not be affected except under serious conditions.

4.4.1.3 Concept Evaluation

Using simulations, the FAA Technical Center will evaluate the system concept and ATC procedures and assess the impact on controller workload. Simulations will incorporate the layout of a demonstration airport, and controllers from that airport will be trained on the system as part of the evaluation. If the concept is feasible, the FAA will design and test a system prototype.

4.4.1.4 Prototype Development and Installation

The warning-system prototype will have a modular design, allowing reconfiguration and enhancement without major changes. During this stage, the FAA will evaluate various technologies that could serve as the system's vortex-detecting and meteorological-predicting components. To provide data for system verification, the FAA also will deploy two vortex-measuring devices at the demonstration airport: the LDV and the MAVSS.

4.4.1.5 Operational Evaluation

After identifying a test airport, the FAA will proceed with an off-line demonstration of the prototype: Controllers and pilots will observe the suggested spacings without using them in actual operations. Once users are satisfied, an on-line system evaluation will begin.

In its assessment of the prototype, the FAA will consider both capacity gains and user reactions. If the system is operationally acceptable, a specification will be developed.

4.4.1.6 System Specification and Acquisition

The FAA will prepare a specification for production of the wake vortex warning system. Further, the agency will develop a strategy for procuring the systems and for deploying them at capacity-restricted airports. This strategy will be defined after determining the system's design and deployment sites.

4.4.2 Airborne Wake Vortex Sensors

As opposed to a ground-based system, an airborne sensor would detect vortices at altitude and send warnings directly to the pilot; it also would alert the pilot as to the appropriate evasive action to be taken. Investigation of airborne sensors is a NASA activity.

To be effective, an airborne system must detect vortices well below the level needed to roll the aircraft. Existing concepts rely on Doppler shifts produced by the relative radial velocity in the vortex, but since there are no such shifts along the vortex axis during landing or takeoff, these concepts have limited use. Several alternatives appear promising, in particular the simultaneous measure of roll rate, roll acceleration, linear acceleration, and differential angle-of-attack on left and right wings. An early NASA product will be a report on the overall feasibility of airborne wake vortex sensing.

4.5 WAKE VORTEX ALLEVIATION AND MODIFICATION

By modifying aircraft to reduce the strength or duration of wake vortices, hazards could be mitigated and separation standards reduced. In the 1970s, NASA investigated a number of possible design changes (such as blowing concepts, oscillating devices, winglets, and flap/slat alterations), but none was able to eliminate vortices without severe operational penalties. NASA is resuming research in this area, in cooperation with the FAA and the industry.

In a related Small Business Innovation Research program, work is under way to calculate vortex strength and duration from basic aircraft design. If the program is successful, manufacturers may be able to determine an aircraft's vortex characteristics before building it.

4.6 USER EDUCATION

As program products are introduced into the ATC system, the FAA will update all related standards, literature, and training materials. A number of new educational aids will be developed to alert pilots to vortex dangers and to instruct them on hazard avoidance. These pilot aids will include advisories, lectures, and videotapes.

5. FUTURE EVOLUTION

The FAA is making far-reaching changes to the ATC system through its National Airspace System (NAS) Plan. Improvements planned for the 1990s and beyond, such as data-link communications and the Advanced Automation System, will significantly impact the procedures adopted as a result of the Wake Vortex Program; for instance, data link could be used not only to send information to pilots about changes in separations, but also to obtain weather data from airborne sensors. To ensure operational efficiency, products of the Wake Vortex Program will be integrated into the NAS as soon as they are available. This will be accomplished through a coordinated effort of all system users.

6. PROGRAM MANAGEMENT

The Airport Technology Branch of the FAA Technical Center (ACD-110) is the designated Wake Vortex Program Office. This office is responsible for establishing project guidelines, integrating activities, scheduling and budgeting, and coordinating user groups. Under the direction of the program office, several organizations share responsibility for the conduct and planning of specific activities. Contributing organizations include the various FAA offices, Transportation Systems Center, NASA, NOAA, and advisory and working groups.

6.1 FEDERAL AVIATION ADMINISTRATION

Many FAA organizations participate in the Wake Vortex Program, in particular the FAA Technical Center and the Air Traffic services.

6.1.1 Technical Center

In addition to its program management responsibilities, the Technical Center leads many technical and engineering efforts. For instance, an airport simulation facility will support two major activities: analysis of capacity gains and evaluation of warning-system concepts.

6.1.2 Air Traffic Organizations

The FAA's Air Traffic Operations (ATO-320), Air Traffic Plans and Requirements Service (ATR-140), and Flight Standards Service (AFS-430) have contributed to the Wake Vortex

Program Plan and will continue to provide technical expertise. Air Traffic will perform the following activities:

- Assign a liaison to coordinate Wake Vortex Program efforts involving air traffic controllers, ATC centers, and other ATO resources.
- Aid in developing warning-system operational requirements.
- Provide experienced controllers (initially from the warning-system demonstration airport) to support simulation efforts at the Technical Center.
- Ensure controllers' support for evaluating the warning system at the demonstration airport.

The Air Traffic Plans and Requirements Service and the Flight Standards Service will:

- Assign a liaison to the Wake Vortex Program Office.
- Specify requirements for modified separation standards and define a process for issuing new standards.
- Work closely with the program team developing the wake vortex warning system and new separation standards to ensure that all requirements are met.

6.2 TRANSPORTATION SYSTEMS CENTER

The Transportation Systems Center (DTS-53) will offer overall support to the FAA Technical Center. Specific tasks will be to

- Recondition the LDV and develop an intermediate MAVSS for use at the Idaho Falls test site.
- Participate in tower fly-by tests at Idaho Falls.
- Upgrade the LDV and GWVSS and develop the long-line MAVSS for deployment at the data-collection airport.
- Acquire vortex measurements at the data-collection airport and analyze this data.
- Develop the ground-based wake vortex warning system.
- Test the warning system at the demonstration airport.

6.3 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA will conduct the following program activities:

- Develop computational fluid-dynamics models of wake vortex formation and decay.
- Model vortex hazards to determine aircraft responses to encounters.
- Analyze and model atmospheric factors such as turbulence and winds.
- Explore the feasibility of airborne wake vortex sensing.
- Study vortex stability and alleviation.

6.4 NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

In support of the Wake Vortex Program, NOAA will:

- Assist with designing, developing, and operating meteorological systems.
- Modify the instrumented tower at Idaho Falls and install test equipment.
- Participate in tower fly-by tests.
- Collect and process vortex data on new-generation aircraft during tower fly-by tests.

6.5 ADVISORY AND WORKING GROUPS

To ensure program effectiveness, the FAA will form a Technical Advisory Committee and a Wake Vortex Working Group.

6.5.1 Technical Advisory Committee

This committee will offer technical advice to the Wake Vortex Program Manager. Chaired by the program manager, the committee will include representatives from the FAA and from other government organizations.

6.5.2 Wake Vortex Working Group

A working group will facilitate user participation in the Wake Vortex Program. Members will represent key industry organizations, including the Airport Operators Council International, American Association of Airport Executives, Air Transport Association, Air Line Pilots Association, Allied Pilots Association, National Air Traffic Control Association, Aircraft Owners and Pilots Association, American Helicopter Society, and Helicopter Association International. The advice of the working group will be an integral part of the program, particularly in the operational testing phase.

7. SCHEDULE AND DECISION POINTS

Figure 2 is a program schedule for fiscal years 1990 to 1997. Depicted are the beginning and end of activities, as well as any milestones or decision points. Some efforts started in FY 1989, before the initial date on the schedule. Several will continue beyond FY 1997.

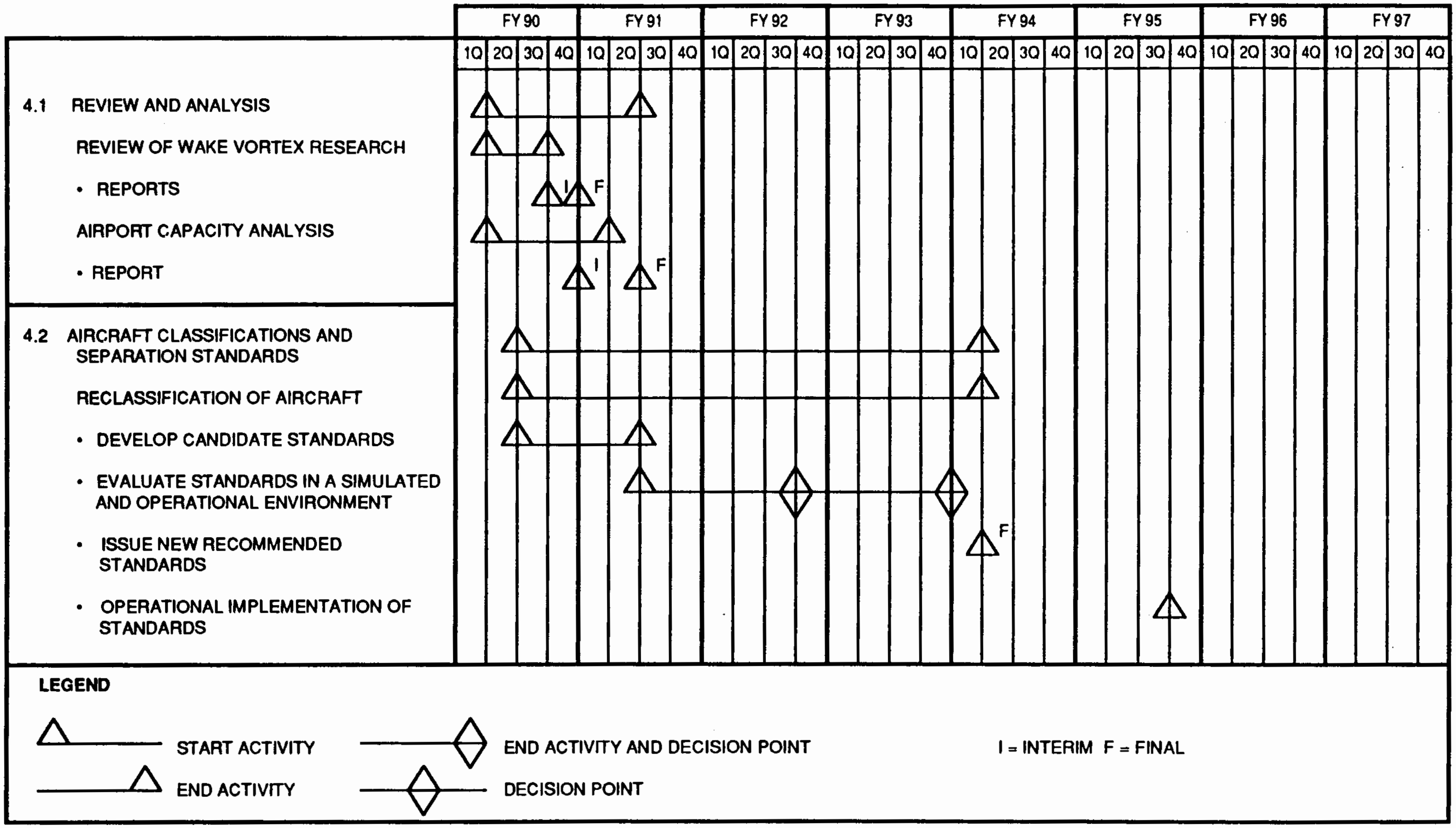


FIGURE 2. WAKE VORTEX PROGRAM SCHEDULE

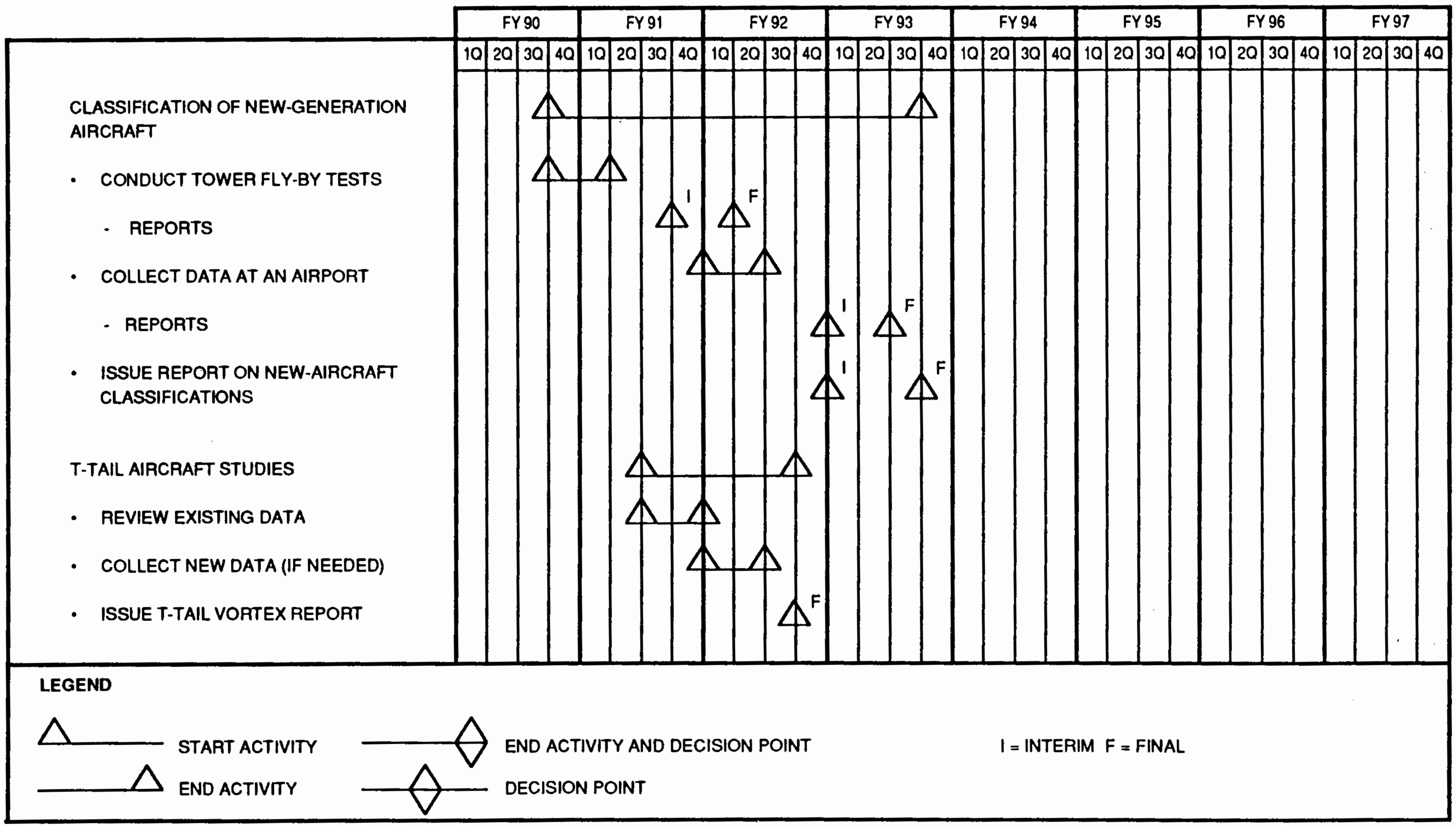


FIGURE 2. WAKE VORTEX PROGRAM SCHEDULE (CONT.)

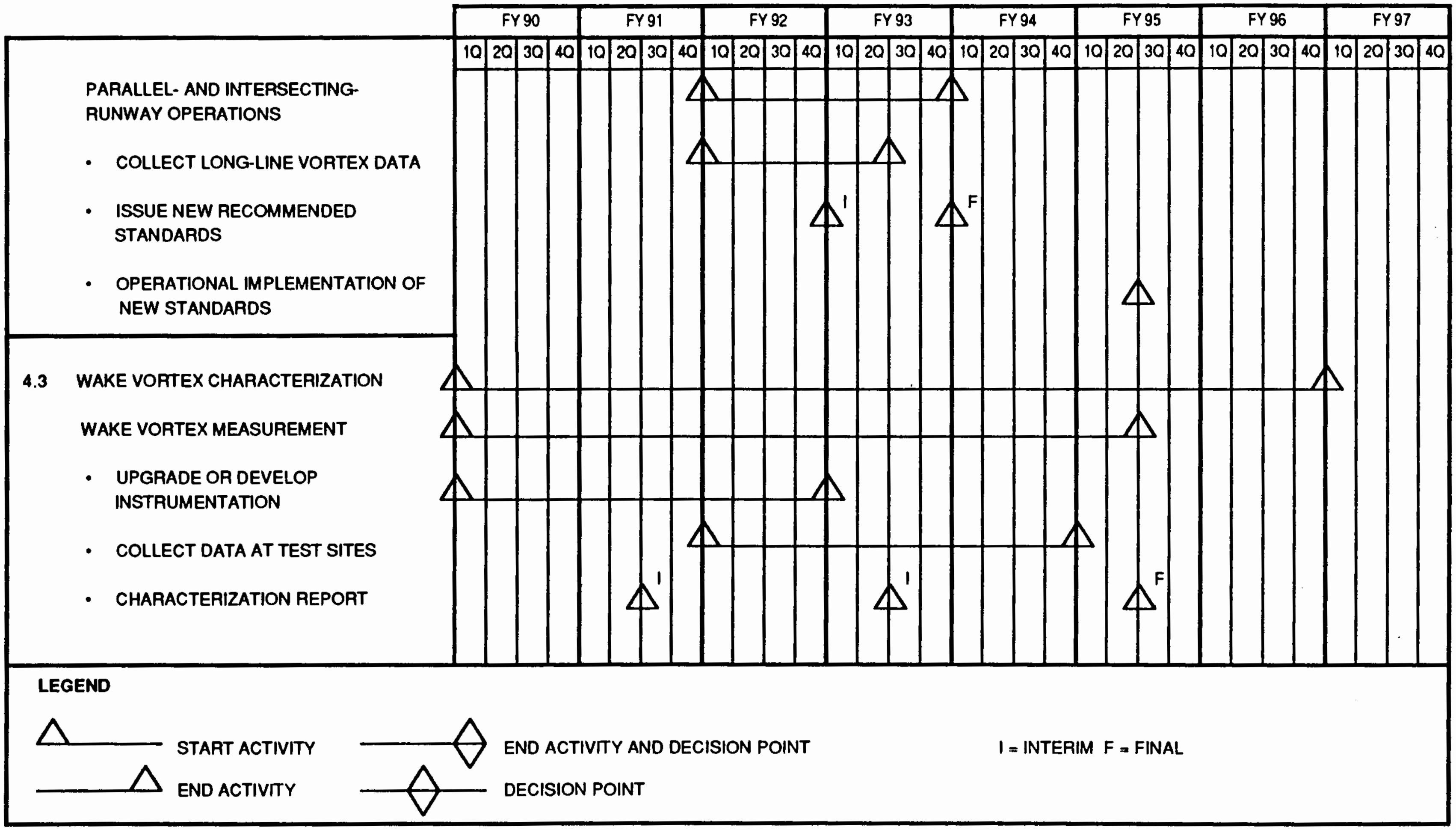


FIGURE 2. WAKE VORTEX PROGRAM SCHEDULE (CONT.)

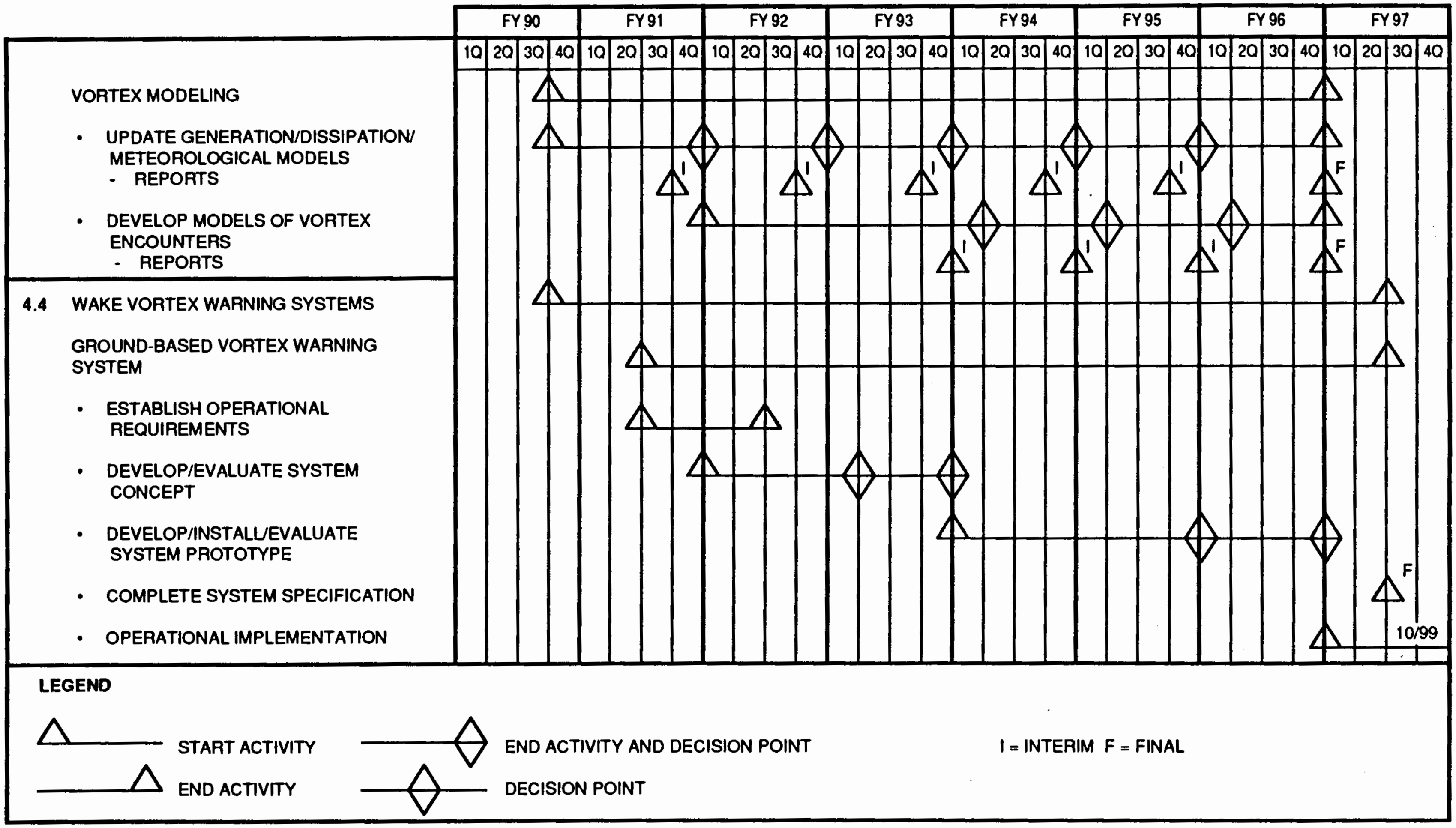


FIGURE 2. WAKE VORTEX PROGRAM SCHEDULE (CONT.)

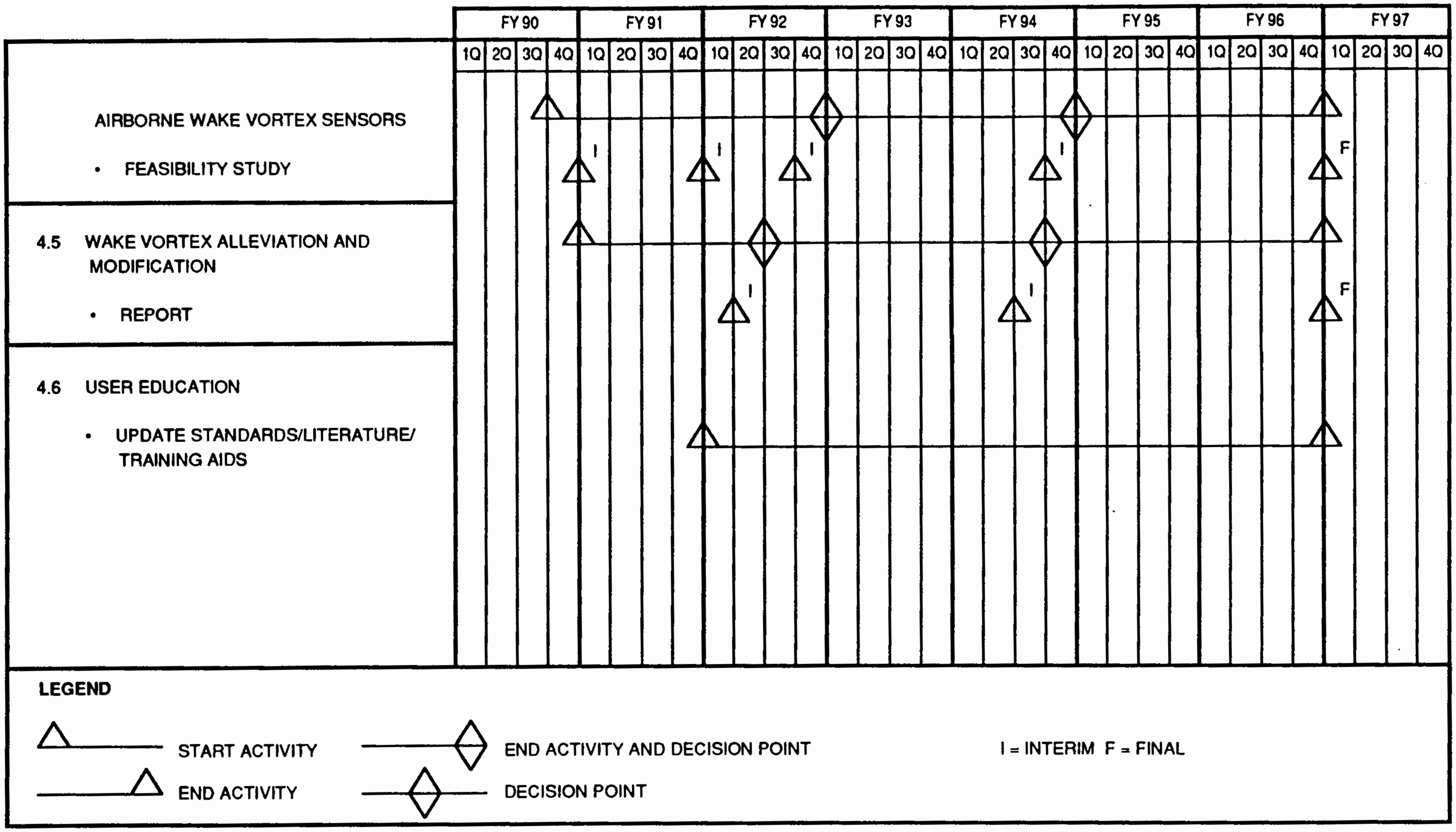


FIGURE 2. WAKE VORTEX PROGRAM SCHEDULE (CONT.)

8. FUNDING

The following table presents the estimated funding needed to accomplish program objectives over a 7-year period:

TABLE 1. WAKE VORTEX PROGRAM FUNDING ($M)

	FY 90	FY 91	FY 92	FY 93	FY 94	FY 95	FY 96
FAA	2.6*	2.1*	5.5	5.4	4.8	4.7	4.3
NASA	--	--	3.0	3.5	4.5	4.5	3.5
TOTALS	2.6	2.1	8.5	8.9	9.3	9.2	7.8

* Includes FAA funding for NASA activities.

APPENDIX A
SUMMARY OF CURRENT KNOWLEDGE OF VORTEX BEHAVIOR

This appendix presents an overview of what is currently known about wake vortex behavior. For an extensive bibliography, please contact the Wake Vortex Program Office.

OVERVIEW

A wake vortex originates from the swirling motion produced by the wing of an aircraft as it produces lift. This vorticity is resolved into two components, one streamwise (oriented with the direction of flight) and the other cross-streamwise (aligned perpendicular to the flight path). The streamwise portion, a manifestation of the lift on the wing, forms the trailing vortices. The cross-stream component is associated with the viscous profile drag of the wing and represents the wake momentum deficit; this component imposes an axial velocity upon the vortex, thereby contributing to its decay.

The generation and decay of a wake vortex occur in stages. In the simplest case, that of a "clean" wing with no areas of abrupt change in lift or drag, the wing vorticity (both streamwise and cross-streamwise) is first shed in an approximately flat sheet, with a width roughly corresponding to the wingspan. The sheet then begins to roll up into a scroll-like shape, until most of the vorticity is concentrated in two circular cores. A number of interactions may occur in or between these cores, creating instabilities that may cause the wake to rapidly break up. If there are no instabilities, the final regular decay of the vortex takes place. At this point, under the influence of atmospheric and aircraft-induced turbulence, the cores expand to fill an elliptical region of vorticity.

These processes are far more complex during takeoff and landing, due to the strong disturbances induced by flaps, engine thrust, and landing gear. The aircraft wing may contain significant regions of concentrated streamwise or cross-streamwise perturbations, possibly leading to the formation of more than one vortex pair. Moreover, the different phases of generation and decay may be either delayed or accelerated.

While aerodynamics dominates the roll-up process, the ambient atmosphere (wind, temperature, turbulence) eventually dictates how vortices behave. To understand this behavior, it is therefore critical to think of vortex interaction with the environment as a statistical process.

VELOCITY FLOW FIELD

The typical viscous vortex is characterized by a swirling flow field with approximately circular streamlines. The tangential velocity along these streamlines varies from 0 at the center to a maximum of 50 percent of the flight speed, and then decreases inversely with the increase in radius. (The core radius is usually defined as the distance from the center at which the maximum tangential velocity occurs.) Once the velocity profile is known, other characteristics can be calculated that define the vortex hazard, including circulation profile and average circulation up to a particular radius.

LATERAL MOTION

The lateral movement of a wake vortex is determined by the ambient winds. At high altitudes, the speed of the lateral motion is equal to the crosswind speed. As vortices descend, this movement is strongly affected by the proximity of the ground. With very calm winds (0 to 1 knots), the vortices tend to move in opposite directions away from the extended runway centerline, at speeds of about 2 to 4 knots. At higher crosswind speeds (more than 7 knots) both vortices move in the direction of the crosswind, with the downwind vortex traveling at a slightly higher speed and the upwind vortex moving at a lower speed. When the crosswind is between these speeds (3 to 5 knots), the lateral action of the upwind vortex becomes difficult to predict: although the downwind vortex moves away from the centerline, the upwind vortex may either move away slowly or stall, creating the potential for a hazardous encounter. In such instances, vortex motion depends on many factors, including the generating aircraft, vortex height, and wind variability.

VERTICAL MOTION

The initial descent rate of a vortex is directly proportional to the weight of the aircraft and inversely proportional to the flight speed and the square of the wingspan. Typically, vortices descend at this initial speed for about 30 seconds, with the rate then decreasing until it approaches 0. (The reduction in the descent rate is caused by the entrainment of the outer flow into the top of the vortex cell and by the shedding of the cell vorticity in the wake, removing both vorticity and momentum from the cell.) Near the surface, the presence of the ground arrests the descent, and the vortices level off at a height equal to about one-half of the wingspan. In unstable atmospheres the wakes may rise, probably because they are carried upward by the considerable vertical currents that accompany instability; the high turbulence that naturally occurs in such an unstable atmosphere results in a very brief life for these wakes.

DECAY PROCESSES

After roll-up is complete, the wakes from high-aspect-ratio aircraft form a pair of coherent, axially symmetrical line vortices. These vortices ultimately decay into random turbulence through a variety of processes, all of which depend upon atmospheric conditions.

The basic vortex pair is subject to two types of instability: sinuous, or "Crow," instability, and core bursting. Sinuous instability causes the spacing between the two vortices to become modulated, with a spatial wavelength of about six times the wingspan; eventually, their cores link to form highly convoluted rings. Bursting is a poorly understood process during which the vortex core suddenly expands. Such bursts may be observed to travel along the cores of smoke-marked vortices.

Whether or not these instabilities occur, the final decay of the vortex is caused by turbulent diffusion; however, data often indicate the persistence of a laminar vortex core while the surrounding vortical motion is dissipated through diffusion. When atmospheric turbulence is stronger than the intrinsic turbulence of the vortex, it enhances the decay process. Sinuous instability is particularly sensitive to ambient turbulence.

INFLUENCES OTHER THAN WIND

In addition to ambient wind, two factors are known to have an impact on vortex behavior: aerostatic forces and atmospheric stability.

Aerostatic Forces

The tilting or banking of the vortex pair has been observed both at altitude and in ground effect. In tests with light aircraft, long segments of the wake occasionally rolled past the vertical, probably due to crosswind shear and shear gradients. When the wake tilted in ground effect, the upper (generally downwind) vortex appeared to break up well ahead of the other, often leaving one vortex drifting alone for some time before it decayed.

Vortex buoyancy is the result of aerostatic forces imposed by virtue of the difference between the air density within the vortex and that of the surrounding atmosphere. Sources of this difference are static underpressure of the vortex, entrainment of hot exhaust gases from the engines, and descent through a nonadiabatic atmosphere. In general, the effects of these aerostatic forces on vertical wake motions appear to be less significant than the impacts associated with turbulence, which could overwhelm the buoyancy effect.

Atmospheric Stability

The predominant effect of atmospheric stability appears to be indirect, and is associated with the vertical air currents caused by atmospheric mixing. Under stable atmospheric conditions this mixing is suppressed, resulting in reduced air motions and fewer effects on the movements of vertical wakes. In an unstable atmosphere, however, vertical activity and resulting wake motions are amplified, causing vortices to rapidly decay. Near the ground, wake vortices do not exhibit such extreme behavior; under stable conditions and reduced thermal activity, the vortex pair undergoes more orderly motions, which are fairly well understood. Since these same factors are conducive to wake persistence, they are of extreme interest in an operational sense.