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Aircraft Wake Vortices: An Assessment of the Current Situation

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16. Abstract

The state of knowledge about aircraft wake vortices in the summer of 1990 is summarized. With the advent of a new FAA wake vortex program, the current situation was assessed by answering five questions: (1) What do we know about wake vortices, (2) what don't we know about wake vortices, (3) what are the requirements and limitations for operational systems to solve the wake vortex problems, (4) where do we go from here, and 5) why do we need to collect more wake vortex data.

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PREFACE

After many years of dormancy, the Aircraft Wake Vortex Program in the United States has been reinstituted. The driving force is that commercial aviation has increased to the point that airports are or are becoming capacity limited. DOT's recent (February 1990) statement of national transportation policy ("Moving America, New Directions, New Opportunities") states that "21 primary airports each now experience more than 20,000 hours of annual flight delays at a yearly cost to airlines and U.S. businesses of at least $5 billion; by 1997, 33 airports are forecast to experience this level of delay."

In June 1981, the author published a Project Memorandum titled "Background Paper, Aircraft Wake Vortex Program," FA186-PM-81-38, which proposed alternative strategies for the wake vortex program based on the then current knowledge of wake vortices and the abortive attempt to introduce a simple vortex advisory system into the air traffic control system. The FAA elected at that time to terminate wake vortex research efforts. With flight delays ever increasing, the FAA has decided once again to establish a program to address wake vortex issues. The advent of the new wake vortex program inspired the preparation of this assessment of the situation. The current document used the 1981 memorandum as a starting point; the material herein is an update of the previous report bringing the reader to the Summer of 1990 by addressing the same four questions:

(1) What do we know about wake vortices?
(2) What don't we know about wake vortices?
(3) What are the requirements and limitations for operational systems to solve the wake vortex problem?
(4) Where do we go from here?

Extensive data was collected in the 1970's, so a natural additional question is:

(5) Why do we need to collect more wake vortex data?

It is the intent of this report to answer these questions by assessing the current state of wake vortex knowledge and the operational issues surrounding potential wake vortex systems.

It is a pleasure to acknowledge the helpful comments from Rick Page, Ed Spitzer, George Greene, Dave Burnham, and especially Robert Machol on various drafts of this assessment report.

METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0		1		2		3		4		5		6		7		8		9		10					
CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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LIST OF ACRONYMS

AIM	Airman's Information Manual
ALPA	Air Line Pilots Association
ATC	Air Traffic Control
CW	Continuous Wave
DAVSS	Doppler Acoustic Vortex Sensing System
DEN	Denver Stapleton International Airport
DOT	Department of Transportation
FAA	Federal Aviation Administration
FM	Frequency Modulated
GWVSS	Ground-Wind Vortex Sensing System
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport
LDV	Laser Doppler Velocimeter
MAVSS	Monostatic Acoustic Vortex Sensing System
MLS	Microwave Landing System
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
PANS	Procedures for Air Navigation Services
PAVSS	Pulsed Acoustic Vortex Sensing System
RVR	Runway Visual Range
SEA	Seattle-Tacoma International Airport
SFO	San Francisco International Airport
US	United States
VAS	Vortex Advisory System
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VNTSC	John A. Volpe National Transportation Systems Center

1. INTRODUCTION

The growth of aviation has established a great demand for airport facilities to accommodate increased air traffic not only safely but efficiently. Optimum use of the facilities requires that every possible effort be expended to develop automation capabilities. The Federal Aviation Administration (FAA) is working toward the upgrading of its air traffic control system with the simultaneous goals of maintaining or improving safety, constraining or reducing operating costs, improving performance and productivity, and meeting energy conservation and environmental needs. Aircraft wake vortices represent an obstacle that must be confronted and overcome before many of the potential benefits of system improvements can be realized. Unless the adverse effects of wake vortices can be substantially reduced, air transportation's future growth potential will be seriously restricted.

The airport is the most critical element in the National Airspace System with respect to capacity limitations. Present and predicted demands being placed on airports cannot be met by indiscriminate construction of new runways and airports in the present ecologic, economic, and social environment. Capacity has actually been declining in recent years because of noise restrictions and wake-vortex separation requirements. The capacity loss coupled with increased traffic has resulted in significant increases in delays and delay-related fuel consumption.

The capacity of an airport to accommodate aircraft depends on such factors as the weather, the number and configuration of runways, the mix of aircraft types, and the spacing required between aircraft to ensure that safety is not compromised. Airports can achieve an increase in capacity with such improvements as dual-lane runways, the MLS, an improved beacon system, the automation of the terminal radar vector service, reduced separation between independent parallel runways, and reduced longitudinal separation on takeoff and final approach. The technology exists to develop the landing aids, but until the wake vortex problem has been mitigated, these improvements cannot be used to their full potential. Wake vortices and the associated separations required to avoid an aircraft upset tend to cancel out the potential gains from the major FAA efforts geared to increasing system capacity.

All aircraft generate trailing wake vortices as a direct consequence of the generation of lift. Although the phenomenon of aircraft wake vortices has been known since the beginning of powered flight, the introduction of the wide-bodied jets with their increased weight and hence stronger vortices rekindled the FAA's interest in the phenomenon.

Aircraft are classified for vortex purposes into three groups according to the maximum certificated gross takeoff weight:

Group	Max. Certificated Gross Takeoff Weight, W
Small	$W \leq 12{,}500$ lb
Large	$12{,}500$ lb $< W < 300{,}000$ lb
Heavy	$300{,}000$ lb $\leq W$

Before 1970, landing aircraft were required to maintain at least 3-nautical-mile separations under IFR conditions. The separation standard was based primarily on radar-operating limits and, to a lesser extent, on runway-occupancy limitations. There were no separation requirements imposed because of vortex considerations. With the introduction of the wide-body jets, the wake-vortex hazard potential increased significantly. Accordingly, the FAA in March 1970 increased the separation standards behind the Heavy jets. By 1973 the standards had evolved to 4 nautical miles for a following Heavy aircraft and to 5 nautical miles for a following non-Heavy aircraft. The international community followed the FAA lead and formally adopted the increased separations behind Heavy jets in 1978 with the approval of Amendment 10 to the ICAO Procedures for Navigation Services --- Rules of the Air and Air Traffic Services (PANS-RAC, Document 4444). The U.S. standards were revised in November 1975 by requiring the addition of an extra nautical-mile separation at runway threshold for following Small aircraft. These increased separations obviously lead to additional delays and a decrease in the capacity and efficiency of the airport system, but the separations were imposed to preclude a hazardous vortex encounter. Recently, Air Traffic has permitted separations to be reduced to 2.5 nautical miles inside the final approach fix when the leading aircraft's weight group is the same or less than that of the trailing aircraft (e.g., a Large following a Large or Small), but there are a number of restrictions that must be met (e.g., Heavy aircraft and the B-757 are permitted to participate in the separation reduction as the trailing aircraft only).

The factor that now dominates the minimum allowable in-trail spacing between aircraft during landings and takeoffs is the hazard caused by the wake vortices shed by aircraft. These vortex wakes of aircraft persist long enough to force following aircraft to delay their arrival until the vortex wakes shed by previous aircraft have either descended below or been blown out of the flight corridor or have decayed to harmless levels. The current minimum separation distances are:

Following aircraft	Wake-generating aircraft		
	Small	Large	Heavy
Small	3 n.mi.	4 n.mi.	6 n.mi.
Large	3 n.mi.	3 n.mi.	5 n.mi.
Heavy	3 n.mi.	3 n.mi.	4 n.mi.

and are based primarily on observations of the lifetime and motion of wake vortices at airports.

Two major approaches have been pursued in the effort to reduce or eliminate the impediment on air traffic flow caused by wake vortices. One approach is to modify the generating aircraft so as to break up the vortices or alter their characteristics and thereby to decrease the potential hazard caused by them. The FAA has supported NASA in their efforts to disperse the vortex and accelerate its decay by modifications to the vortex-generating aircraft. The second approach is to develop a system which will predict and/or detect the presence of a vortex from a leading aircraft and thereby determine the minimum safe (vortexwise) separation for a following aircraft. In concept, the system will ensure that aircraft will avoid inadvertent encounters with hazardous vortices by tailoring aircraft spacings to be commensurate with the vortex hazard. The FAA has pursued this latter approach with the assistance of the John A. Volpe National Transportation Systems Center (VNTSC).

The wake vortex problem is complex because of the large number of variables. Setting aside the various operational scenarios, the problem involves the parameters introduced by the vortex-generating aircraft, by the vortex-encountering aircraft, and by the intervening atmosphere. The vortex is initially characterized by the parameters of the vortex-generating aircraft (weight, wingspan, speed, flap and spoiler settings, proximity to the ground, engine thrust, lift distribution, etc.). The encounter (safe or hazardous) is characterized by the parameters of the following aircraft (speed, wingspan, roll control authority, phase of flight, etc.). The meteorology (wind, crosswind, atmospheric stability, turbulence, etc.) plays a leading role in determining how long a vortex remains hazardous.

Much has been learned about aircraft wake vortices. During the 1970's, NASA conducted many tests of vortex alleviation techniques using wind tunnels and water channels and full-scale flight tests. The vortices from over 70,000 landing aircraft operations have been measured and analyzed with respect to the attendant meteorological conditions by VNTSC under the aegis of the FAA. During the 1980's, there was comparatively little aircraft wake-vortex research in the US. NASA's low-level program emphasized understanding the oftentimes perplexing alleviation test data and the development of vortex behavior models. The FAA's low-level program addressed helicopter vortices and further analysis of the 1970's data, but little was published due to fiscal constraints.

The purpose of this report is to address briefly five questions:

(1) What do we know about wake vortices?
(2) What don't we know about wake vortices?
(3) What are the operational requirements and limitations for systems to solve the wake vortex problem?
(4) Where do we go from here?
(5) Why do we need to collect more wake vortex data?

This report was prompted by the resurgence of the wake vortex program in the FAA. But, one must learn from history --- there were a number of problems and constraints uncovered when operational implementation of a simple vortex avoidance system (the Vortex Advisory System) was attempted at Chicago O'Hare. Many of these problems and constraints will be confronted when any system is proposed for use in the air traffic control system. The report will also review our state of knowledge about wake vortex behavior as a guide to future data collection. (A detailed review of aircraft wake vortex knowledge is underway; it will be an update of the 1977 state-of-the-art review (Ref. 26).)

Sections 2, 3, and 4 address the present knowledge about vortex behavior; Section 5 examines the gaps in this knowledge; Sections 6 and 7 describe the various systems that have been considered and some of the problems faced; and Section 8 addresses various alternative paths that the vortex program could follow. Section 9 presents a recommended path for a wake-vortex program. This assessment report is a first step in developing an agency-integrated aircraft wake-vortex program.

2. HISTORICAL DEVELOPMENT OF VORTEX PROGRAM

The purpose of this section is to put the vortex program into its proper perspective. Beginning in 1970 the vortex problem was one of safety --- what can one do to prevent a hazardous encounter? Flight tests by NASA and the FAA at altitude (Refs. 1 through 8) found significant vortex-imposed rolling motions 10 nautical miles behind Heavy jets. Does the vortex hazard persist for such distances when the aircraft are near the ground during approach, landing, and departure operations? In May 1972 a DC-9 crashed on final approach at Greater Southwest Airport; the cause was an encounter with a vortex from a DC-10 doing touch-and-goes, two nautical miles ahead of the DC-9 (Ref. 9). Most of the vortex-caused accidents occurred on final approach (Ref. 10), so the early effort was devoted to learning about the vortex phenomenon during landing operations; but first the tools for such work had to be developed. In early 1973 the FAA Air Traffic Service requested that the separation standards be reviewed, as the British had promulgated standards that included a 10-nautical-mile separation for a Small behind a Heavy. By late 1973 enough data were collected to demonstrate that the ATC separation standards for landing commercial airliners were indeed adequate for preventing hazardous vortex encounters. In 1975, at the instigation of the FAA Systems Engineering and Development Service, the landing separation standards were revised for Small following aircraft based on analysis of the vortex data (the addition of an extra nautical-mile separation at runway threshold). About this same time, the emphasis of the program shifted from safety to increasing capacity (without jeopardizing safety) as part of the Upgraded Third Generation Air Traffic Control System.

Of the approximately 68,000 aviation accidents that occurred in the United States during the 15-year period 1964-1978, wake vortices were cited by the NTSB as a cause or factor in 225 accidents. There were 116 landing accidents (26 fatal), 50 takeoff accidents (6 fatal), and 59 inflight accidents (6 fatal). Eliminating the 46 inflight cropduster accidents, an average of 12 accidents per year were listed as vortex related. Approximately two-thirds (116) of the accidents occurred while the victim aircraft was landing, and three-quarters (89) of these accidents occurred with the victim aircraft following another landing aircraft to the same runway. Most of the latter accidents occurred when the victim aircraft was between the middle marker and touchdown. The accident aircraft vary in size from a DC-8 (serious injuries behind an L-1011 descending through the same altitude) and a DC-9 (fatal, following a DC-10 doing touch-and-goes on the same runway, Greater Southwest Airport) to the Cessna 150s. General aviation aircraft weighing less than 12,500 pounds have been the primary victims of the vortex problem. Since the separation standards were increased for following Small aircraft in November 1975, the number of vortex-caused accidents has decreased.

The pre-1970 theories describing aircraft wake vortex characteristics were very simplistic. It was generally understood that (1) the vortex strength depended on the size, weight, and speed of the aircraft; (2) the pair of vortices generally descended after generation and would separate when they approached the ground; and (3) the vortex motion was substantially affected by the ambient wind. However, the lack of field testing prior to 1970, especially of vortices near the ground, precluded an indepth understanding of vortex behavior, particularly decay. Some tests were conducted with a probe aircraft at relatively high altitudes and with aircraft flying past instrumented towers. However, these early tests were limited in scope and did not look at vortices from aircraft in an actual operational environment.

The first years of the wake vortex program at VNTSC saw the development of several sensor systems capable of detecting and tracking vortices near the ground (Refs. 11 through 18). This region was selected for study since this is the area where a vortex could stall in the approach path and thus pose a hazard to a following aircraft with little room to maneuver or recover. It was also the area in which most of the vortex-caused accidents occurred. Various sensing techniques were investigated, including acoustic (Refs. 11 through 12, 19 and 20), electromagnetic (Ref. 11), passive ground-wind measurements (Refs. 11 through 13), pressure (Refs. 12 and 21), and laser Doppler (Refs. 22 through 24). An extensive series of tests was performed in 1972 to test and calibrate the most promising sensors (Refs. 12 and 25).

The large-scale data collection phase of the program began with the installation of several sensor systems at the John F. Kennedy International Airport (JFK) in June 1973 to measure vortices from landing aircraft (Refs. 13 and 25 through 28). Additional newly developed sensors were also tested at JFK (Refs. 22, 29 and 30); the site was closed in January 1977. Other data collection sites were established at Stapleton International Airport (August through November 1973; Refs. 26 through 28), Heathrow International Airport (May 1974 through June 1975; Refs. 26 and 31 through 34), and O'Hare International Airport (July 1976 to August 1981; landing data collection terminated in September 1977; Refs. 26 and 35 through 37). A combined total of over 70,000 runs were obtained from these test sites; these runs examined the behavior of vortices from landing aircraft between the middle marker and the runway threshold. A test site was operated at Toronto International Airport between August 1976 and August 1977 for the study of vortices shed by departing aircraft (Ref. 38). Over 5000 runs were obtained. To expand the data base on takeoff vortices, a site was established at O'Hare and data collection commenced in December 1979. Over 15,000 runs were recorded, and the site was closed in November 1980.

Extensive analysis of the landing data led to the concept of the Vortex Advisory System (VAS). The current landing separations

were shown to be safe as they are oftentimes very conservative. Thus, opportunities exist to regain capacity by compressing the standards during those times when vortices do not pose a threat to a following aircraft. The VAS (Refs. 26 and 35 through 42) used measurements of the ambient winds in the middle marker region to indicate when vortices had either moved away from the approach path of a following aircraft or had dissipated to an innocuous level.

A demonstration VAS was designed, developed, and in 1977 was installed at O'Hare (Ref. 43 and 44). A detailed safety analysis was completed and published (Refs. 45 through 47), and a measurement program completed verifying the analytical model of the VAS which permits VAS utilization from the outer marker to touchdown (Ref. 35). When operational implementation of the VAS was attempted, problems and constraints were encountered. The problems were primarily procedural in nature. The imposed constraints never surfaced in the numerous interactions with the user community (e.g., Ref. 46) until the commencement of operational implementation. The VAS problems and constraints are discussed in Section 7. A reassessment of the direction of the vortex program is needed in light of the problems and constraints, as most of them will pertain to any solution to the vortex problem.

3. VORTEX SENSORS

A number of different sensing systems have been developed for detecting and measuring wake vortices. This section will describe the ground-based sensors which were developed primarily as research tools for collecting vortex behavior data, and discuss airborne and ground-based sensors as they pertain to operational systems.

3.1 GROUND-BASED DATA COLLECTION SENSORS

The first measurements of wake vortex velocity profiles made use of towers instrumented with hot-wire anemometers (Refs. 48 through 52). Dedicated aircraft flew at low altitude past the tower on the up-wind side. Vortex decay was studied by varying the lateral offset of the aircraft and hence the age at which the vortex drifts through the tower. The instrumented-tower measurements suffered from sensitivity to the ambient wind and the effects of the tower on the wake; the technique also permitted only one measurement of a vortex for each aircraft passage.

Because of the impracticality of using dedicated flight tests to amass statistics on vortex transport and decay, subsequent data collection made use of remote sensors which could be deployed at airports during normal operations. The first sensors (Ground-Wind Vortex Sensing System (GWVSS), Pulsed Acoustic Vortex Sensing System, and an early version of the Laser Doppler Velocimeter (LDV)) could measure vortex position but not strength. The next generation of sensors (Monostatic Acoustic Vortex Sensing System (MAVSS) and Doppler Acoustic Vortex Sensing System (DAVSS)) could also measure strength. Eventually, techniques for deriving vortex strength from data collected by the LDV and GWVSS were developed.

The GWVSS consisted of an array of single-axis anemometers located on a baseline perpendicular to the flight path (Refs. 18, 26, and 53). They detect the presence of a wake vortex by the wind induced by the vortex near ground level. The positions of the most positive and most negative peaks in the crosswind velocity component give an accurate indication of the lateral positions of the two counterrotating vortices.

The success of the GWVSS in tracking wake vortices stems from the induced motion of a vortex pair. After generation, the vortices descend toward the ground. When they approach the ground, they separate (assuming no crosswind) and level off at a height equal to about one-half their initial spacing (initial spacing is about three-quarters of the wingspan). The GWVSS detection threshold for vortices at their equilibrium height and in light and relatively nonturbulent winds appears to be well below the hazard threshold; thus, any system based on GWVSS tracking is inherently conservative. However, vortices can rebound above the

equilibrium height; the accuracy of the GWVSS in this situation (particularly when the winds are moderate to strong and turbulent) is in question. A technique was demonstrated for automatic tracking and for extracting vortex strength from GWVSS data (Ref. 53). Although only partially successful, such a technique could greatly extend the usefulness of the GWVSS.

The PAVSS detects the acoustic signal refracted by a vortex core (Refs. 18 through 20, 26, 29, and 54 through 56). Although the PAVSS gave accurate measurements of vortex height, the system was abandoned because it could not detect diffuse vortices from some aircraft types (B-707s and DC-8s) and because it gave no reliable information on strength or decay.

The LDV probes the atmosphere with a beam that can be scanned in range and angle (Refs. 18, 22 through 24, and 26). The radiation which is backscattered from aerosol particles in the focal region is spectrally analyzed to yield the velocity component along the beam. The LDV gives excellent angle resolution but poor range resolution. The original scan mode of the LDV could track vortices reasonably well, but gave only a vague indication of strength. After a new scan mode and a new data-processing procedure were developed (Refs. 18, 35, and 57), the LDV produced excellent vortex velocity profiles from which vortex strength can be calculated. The LDV produces its best measurements on vortices located about 600 feet overhead. Measurements on vortices at low elevation angles suffer from sensitivity to the ambient wind and mixing of the signals from the two vortices. The LDV is the only sensor currently used that can continuously track and measure a vortex until it decays.

The MAVSS consists of a vertically pointing acoustic beam in which pulses of acoustic energy are backscattered from temperature fluctuations in the atmosphere (Refs. 18, 26, 36, 58, and 59). Spectral analysis of the returns yields a vertical profile of the vertical velocity in the atmosphere. Since the ambient wind is horizontal near the ground, the MAVSS measurements of vortex velocities are not affected by the wind. The tangential velocity profile of the vortex is measured as the vortex drifts through an array of vertical beams. The MAVSS is operated with a range of 200 to 300 feet, and averages the velocity over a volume about 10 feet high and 6 feet in diameter. The MAVSS gives good measurements of the strength of moving vortices, but is much less useful for stalled vortices (a dense array of MAVSS units would be needed to deal with stalled vortices).

The DAVSS features a receiving antenna with multiple receiver beams in the form of a fan (Refs. 18, 26, 30, and 60). A variety of transmitter configurations using CW or pulsed signals was tested. The most useful configuration was a pulsed monostatic configuration (much like the MAVSS) with all antennas located near the runway centerline. This configuration showed promise for

measuring stalled vortices, but was abandoned because of software problems and the cumbersome nature of the hardware.

3.2 OPERATIONAL AIRBORNE AND GROUND-BASED VORTEX SENSOR SYSTEMS

Potential airborne and ground-based sensors can be divided into three categories: a) remote sensors which measure velocity, b) remote sensors which detect some tracer in the wake which will dissipate when the vortices are no longer a hazard, and c) sensors which detect the proximity of some feature of the wake. The sensors which depend upon some tracer in the wake (such as infrared sensing of heat, ultraviolet sensing of nitric oxides, or radar sensing of refractive index fluctuations) are unlikely to be very useful because of the difficulties in relating hazard to sensor signatures. The local proximity sensors have similar problems as well as the problem of insufficient warning time. The proven velocity sensors (LDV and Doppler radar) are not practical for airborne applications because they measure the velocity component along the line of sight, whereas hazardous vortex velocities are transverse to the line of sight. However, novel techniques for measuring transverse velocities offer some promise.

Of all the ground-based velocity-measuring sensors developed to date, at this time only the GWVSS represents a sensor which would be useful as an operational vortex sensor. Reliable rapid processing could be based on available algorithms (Ref. 53). The system is simple, inexpensive, and easily installed everywhere except over the actual runway surface. The GWVSS is useful, however, only when the vortices are less than about 200 feet above the ground (between runway threshold and about a half mile from the threshold). The acoustic systems suffer from noise, rain, and snow problems and are far from having reliable real-time processing. The LDV has not yet been engineered for unattended operation, requires substantial human intervention in the data processing, and has limited utility in conditions with low ceilings or poor visibility.

Doppler radars can detect wake vortices if looking at them from the side. FM-CW monstatic radars (Refs. 61 and 62) and certain bistatic radars have shown promise. The observed signatures, however, are yet to be understood. The range capabilities of these sensors make them candidates for studying vortices at the outer marker and perhaps beyond. It may be possible to track both vortices off an incoming aircraft.

Sensor-based vortex avoidance systems rely to some extent on predicting vortex behavior rather than solely on direct measurement of wake vortices themselves. The lead time required to set up aircraft spacing on final approach requires prediction of vortex behavior; real-time measurements of the vortices from the preceding aircraft are not sufficient to ensure efficient traffic

flow. To demonstrate that prediction is an inherent part of any system, consider the case of an ideal situation. Suppose that vortices somehow were visible until they no longer posed a hazard. A pilot could use this real-time vortex-tracking information to safely guide his aircraft only by predicting where the vortices will be when his aircraft reaches various positions ahead. The essential point is that, prediction is a component of any system used to avoid a hazardous condition (be it wake vortices or wind shear, downbursts, ground proximity, mid-air collisions, etc.). Either the pilot uses data to make a prediction directly or a sensor system assimilates data and predicts a potential hazardous condition and passes this information to the pilot for action.

4. STATUS OF CURRENT KNOWLEDGE OF VORTEX BEHAVIOR

Any finite lifting wing must leave behind it two counter-rotating trailing vortices, the direction of rotation being such that between these vortices the air moves downwards while outside of them the induced flow is upwards. Very simplistically, these vortices are formed because the pressure of the air above the wing is less than that of the air beneath the wing (hence the lift) and there is a tendency for the air to flow around the wingtip; air below the wing, as it streams backward moves outward, then upward past the wingtip, and finally inward when it gets above the wing. This motion sets up a swirl in the air and generates a vortex just inboard of each wingtip.

The wake vortex originates in the vorticity shed from the generating wing. The vorticity can be resolved into streamwise (oriented with the flight direction) and cross-stream (aligned perpendicular to the flight path) components (Ref. 26). The streamwise portion is the manifestation of the lift on the wing and forms the trailing vortices. The cross-stream component is associated with the viscous profile drag of the wing and represents the wake momentum deficit associated with the profile drag. This component causes an axial velocity to be imposed upon the vortex, and thereby contributes to vortex decay.

The generation and decay of the wake vortex system occurs in stages (Refs. 26 and 63). For simplicity, first consider the simplest case 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 of width roughly corresponding to the wing span. The sheet commences to form a self-induced scroll-like shape (Ref. 64). The rollup process continues until most of the wing vorticity is concentrated in two approximately circular vortex cores. Various interactions may occur in or between these cores creating instabilities which can cause the wake to break up rapidly. If catastrophic instabilities do not occur, final regular decay takes place. Here, under the influence of both atmospheric and aircraft-induced turbulence, theoretical considerations indicate that the cores expand to fill an approximately elliptical region of vorticity (Ref. 63). This simple picture of vortex decay has been used for many years; however, it is now in serious question as detailed measurements (Ref. 111) demonstrate that the vortices decay from the outside inward.

If the wing contains significant regions of concentrated streamwise or cross-stream perturbations (due to control surfaces, flaps, spoilers, landing gear, etc.), there may be more than one vortex pair, and the various stages may develop with different time scales compared to the clean-wing case. The various vortices interact and eventually combine into a single pair (sometimes into

two pair as for the Concorde when flying subsonically). The different stages may be delayed or accelerated. This situation occurs for aircraft in the landing or takeoff configurations. There, strong disturbance effects occur induced by flaps, jet engine thrust, and landing gear (Ref. 65).

This section briefly summarizes the current knowledge of the behavior of wake vortices. Much has been learned about vortex behavior, but there is yet much to be learned. Aerodynamics dominates the rollup process, but the ambient atmosphere (wind, stability, turbulence, etc.) eventually dictates how the vortices behave. Vortex motion and decay are stochastic processes; i.e., the vagaries of the atmosphere and slight changes in aircraft characteristics can lead to different vortex behavior even though it seems that all the conditions are the same. Stochastic processes require extensive data collection to determine the envelope of behavior.

4.1 VELOCITY FLOW FIELD

The general flow field of a viscous vortex is a swirling flow having approximately circular streamlines. The tangential velocity along these streamlines varies from zero at the center to some maximum which may be as great as 50 percent of the flight speed, and then decreases approximately inversely with increase in radius (Ref. 26). The core radius is usually defined as the distance from the center at which the maximum tangential velocity occurs. Some vortices were found to have small cores and high tangential velocities; some had large cores and attendant lower velocities. Quantitative data on vortex flow fields were obtained in the early 1970's by FAA's National Aviation Facilities Experimental Center using an instrumented 140-foot tower and flying various aircraft upwind of the tower. Data were collected on B-707, B-727, B-747, DC-7, DC-8, DC-10, CV-880, L-1011, C-141, and C-5A aircraft (Refs. 48 through 52, and 66 through 73). Based on this extensive data, vortex flow field models were developed. Given the lift distribution on an aircraft wing, the expected flow fields can be calculated. Once the tangential velocity profile of a vortex is known, other useful characteristics of the vortex can be calculated such as the circulation profile and the average circulation up to a particular radius, which can be used in defining the vortex hazard.

4.2 LATERAL MOTION

The horizontal motion of vortices is dictated by the ambient wind. At altitude, the wind is the only influence; near the ground, the ground also has an influence. The lateral motion of vortices is dominated by the crosswind component of the ambient wind; at relatively high altitudes, the speed of the vortex

lateral movement is equal to the crosswind. With no other external influence, these vortices would continue to move at this speed until they completely decayed. However, as the vortex pair descends to the proximity of the ground, the lateral motion is strongly affected by the boundary to a degree which is at least as important as the crosswind. With very calm winds (0 to 1 knots), the two vortices have a tendency to move in opposite directions away from the extended runway centerline with speeds of approximately 2 to 4 knots. At higher crosswinds (greater than 7 knots), both vortices move in the direction of the crosswind with the downwind vortex transporting at a speed slightly higher than the crosswind and the upwind vortex transporting at a speed slightly less than the crosswind. It is the region in between these values (3 to 5 knots) where the lateral motion of the upwind vortex becomes difficult to predict. The downwind vortex moves away from the extended centerline with a slight increase in speed, but the upwind vortex may either very slowly transport away or may stall near the runway centerline. If a vortex stalls near the centerline, the potential for a hazardous situation exists. The vortex motion in the latter case depends on many factors such as the generating aircraft type, vortex height above the ground, variability in the winds, etc.

The extensive data-collection tests at airports showed how vortices move as a function of wind near the ground. These tests led to a wind criterion that could indicate when the wind conditions were such that a vortex could not pose a threat to a following landing aircraft. Vortices were found to move laterally at least 1500 feet under certain conditions, but with seemingly weak strengths at the larger lateral distances. Recent measurements by the Germans at Frankfurt International Airport (Ref. 113) found B-747 vortices that moved laterally 1700 feet and still retained some strength. Motions of vortices were found to be affected by wind gradients and even "bounce" (i.e., descend toward the ground and later begin to rise up somewhat) at times.

4.3 VERTICAL MOTION

The initial descent rate of vortices seems to be adequately described by classical analysis; the rate is proportional to the weight of the aircraft and inversely proportional to the flight speed and to the square of the wingspan. Generally, vortices descend at the initial rate (about 4 knots for a DC-10) for about 30 seconds, and then the rate decreases and finally approaches zero (Ref. 74). The reduction in the descent rate is caused by entrainment of the outer flow into the top of the vortex cell along with a shedding of the cell vorticity in the wake, removing both vorticity and momentum from the cell (Ref. 63). Near the ground, the presence of the ground arrests the descent and the vortices level off at a height of approximately one-half their initial separation.

Descent trajectories have been measured during various atmospheric conditions (Ref. 74). In stable atmospheres, the range of initial descent speeds are within 25 percent of the classical or theoretical rate. Slowing down occurs after about 30 seconds, with descent speeds at 60 seconds typically one-half to three-quarters of the initial values. Wakes in a neutrally stable atmosphere show a fairly rapid descent, with initial speeds often exceeding the theoretical rate. Wakes can rise in unstable atmospheres, probably because they are being carried upward by the considerable vertical currents which accompany instability. The high turbulence which naturally occurs in such an unstable atmosphere usually results in very brief lives for these wakes, however.

4.4 DECAY PROCESSES

After rollup is complete, the wake from high-aspect-ratio aircraft can be accurately described as a pair of coherent axially symmetric line vortices. These vortices ultimately decay into random turbulence through a variety of decay processes which depend upon atmospheric conditions. The basic vortex pair is subject to two types of instabilities: the sinuous or Crow instability (Refs. 63, 75 and 76) and core bursting (Refs. 77 through 79). The sinuous instability causes the spacing between the vortices to become modulated with a spatial wavelength of about eight times the wingspan (Ref. 75). Eventually, the cores of the two vortices link to form highly convoluted vortex rings. Core bursting is a poorly understood process where the vortex core suddenly expands. A burst is observed to travel axially along the core of a smoke-marked vortex. Even through a burst may disperse the smoke marking a vortex, it does not necessarily destroy the coherent circulation of the vortex. For weak turbulence with a large integral scale compared to the separation of the vortices, vortex linking is the dominant mode of vortex instability. However, as the turbulence intensity increases, vortex bursting begins to appear and eventually replaces linking as the dominant mode of instability (Ref. 114). Whether or not these instabilities occur, the final decay of the vortex into random turbulence is produced by turbulent diffusion effects (viscous decay is a much slower process). Vortex decay data often show a laminar vortex core which persists while the surrounding vorticity is dissipated by turbulent diffusion (e.g., Ref. 80).

Atmospheric effects play an important role in driving vortex decay processes. Atmospheric turbulence enhances vortex decay when it is stronger than the intrinsic turbulence of the vortex. The sinuous instability is particularly sensitive to ambient turbulence. There is considerable evidence that a very stable atmosphere (i.e., a temperature inversion) enhances vortex decay; vorticity and turbulence generated on the periphery of the vortex may be responsible (Ref. 80).

The airport tests and dedicated flight tests in cooperation with NASA led to the development of vortex decay models. It was found that many processes were taking place often at the same time (Crow linking, bursting, viscous decay, and "scrubbing" with the ground). Vortices were found usually to decay from the outside inward (Ref. 111), not from the core outward as most fluid-mechanic theories predict; thus, the picture of vortex decay is changing.

4.5 SAFETY CORRIDOR

Analysis of the data from thousands of vortex tracks necessitated that a reference zone be defined in which the mere presence of a vortex could be interpreted as a possible hazard to a following aircraft. The boundaries of this corridor were defined using two considerations. First, it was determined from photographic data recorded at Denver's Stapleton International Airport in 1973 that over 99 percent of landing aircraft in VMC are within 50 feet of the extended runway centerline in the region from middle marker to touchdown (Ref. 27). Second, simulations showed that if a vortex center was farther than 100 feet from the fuselage of the vortex-encountering aircraft, there would be no excessive disturbance to the aircraft (Refs. 81 and 82). Thus, a safety corridor was defined which extended 150 feet to either side of the extended centerline, was indefinite in height, and extended from the middle marker region to touchdown.

A vortex has the highest potential of becoming a hazard to a following aircraft when the ambient crosswind causes the upwind vortex to stall in the safety corridor for times approaching the interaircraft spacing with a height close to the aircraft flight path. It was determined in early tests (Ref. 27) that the vortices from aircraft at heights below about 50 feet tend to decay fairly rapidly, probably due to the rapid interaction of the newly forming vortex with the ground and incomplete rollup. The vortices from aircraft at heights greater than approximately 200 feet have only a small chance of becoming a hazard since they descend out of the flight path. It is the region in between where the stalled vortex can become a problem, and therefore most of the data were collected with sensor lines installed at a distance from runway threshold (typically 1500 feet) where the normal aircraft height would be in the range of 80 to 140 feet.

The vortex data were examined to determine the probability of finding a vortex stalled in the safety corridor. A time of 80 seconds was chosen as a reference as this translates to approximately a 3-nautical-mile spacing for typical aircraft approach speeds (135 knots). It was found that only 5 to 10 percent of the vortices from Heavy aircraft remained in the safety corridor for longer than 80 seconds (Refs. 26, 32, 37, and 83); thus 3-nautical-mile separations could theoretically be used most

of the time. It must be pointed out that vortices observed remaining in the corridor may not represent a hazard since most of this data was obtained with the GWVSS, which yields no indication of vortex strength; detection of a vortex with this system does not necessarily imply a hazardous condition.

4.6 INFLUENCES OTHER THAN WIND

Tilting or banking of the vortex pair has been observed both at altitude and in ground effect. In tests with light aircraft (Refs. 74, 77, and 84), long segments of the wake were observed occasionally to roll past the vertical. It appears that asymmetries in the initial rollup and crosswind shear and/or the rate of dissipation of the background turbulence are responsible for this rolling tendency of vortex pairs (Refs. 74, 85, and 108). When the wake tilts in ground effect, the upper (generally downwind) vortex appears to break up well ahead of the other vortex, often leaving one vortex drifting alone for some time before it decays.

Vortex buoyancy (Refs. 26 and 63) is the aerostatic force imposed on the vortex by virtue of the difference in density between the air contained within the vortex and the surrounding ambient air. The sources of the density difference are static underpressure of the vortex, entrainment of hot exhaust gases from the engines, and descent through a nonadiabatic atmosphere. Overall, the effects of aerostatic forces on vertical wake motions may be of the same order as the dissipative mechanisms associated with turbulence.

The predominant effect of atmospheric stability (Refs. 26 and 84) appears to be the indirect one associated with the vertical air currents resulting from atmospheric mixing. In a stable atmosphere, this mixing is suppressed, resulting in reduced vertical air motions and reduced effects on vertical wake motions. In unstable conditions, vertical atmospheric activity and resulting wake motions are amplified and vortices decay rapidly, as discussed in Section 4.3. Under a strong inversion or a super stable atmosphere, vortices decay quickly. In neutral stability, the stability apparently kills the turbulence.

Near the ground, wake motions 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 and can be approximated analytically (Refs. 26 and 109). These conditions are also the ones of greatest operational interest because these same factors are conducive to wake persistence and thus could pose a threat to an aircraft.

4.7 STRENGTH AND DECAY

A large MAVSS data base on the decay of vortex strength has been collected at O'Hare International Airport for landing aircraft (Ref. 36). One useful method of analyzing the data yields the probability of the vortex strength remaining above a hazard threshold as a function of vortex age. As one would expect, the hazard probabilities decay more slowly as the hazard threshold is decreased. In other words, the weaker a vortex needs to be to be still considered a hazard, the longer one needs to wait before the vortex decays sufficiently to be considered benign. The probability is observed to decay exponentially with the square of the vortex age. This rapid decay accounts for the observed safety of the IFR and vortex separation standards.

The MAVSS vortex decay data were disaggregated to determine the dependence of vortex decay on crosswind, wind speed, and other meteorological parameters. The most important factor is the crosswind. The downwind vortex decays more quickly than the upwind vortex. The latter is also the one which tends to stall near the extended runway centerline. Vortex decay is speeded up by higher ambient winds, presumably because of increased turbulence. The differences in the decay of vortices from landing Heavy and Large B-707s and DC-8s were examined and found to be minimal (Ref. 110), probably indicating that the actual weight of the vortex-generating aircraft is more important than the gross certificated takeoff weight.

4.8 VORTEX ENCOUNTERS

Wake vortex encounters have been studied by both aircraft probes (intentionally flying into a smoke-marked vortex; Refs. 1 through 8, 86, and 87) and by simulations (Refs. 26, 81, 82, and 88 through 93). The dominant vortex hazard appears to be the rolling moment induced on a directly following aircraft wing by the vortex motion. Vortex-induced deviations in roll attitude of greater than 10 degrees were found in simulations by NASA to be unacceptable near the ground (Refs. 92 and 94), although much more severe rolls have been encountered, and survived, at altitude. Computer simulations showed that a wake vortex causes no problems to an aircraft more than 100 feet away from the vortex axis (Refs. 26, 81, and 82). Complete six-degree-of-freedom simulations, as well as aircraft probes, show that the vortex tends to repel an encountering aircraft from a direct penetration of the vortex core. However, the pilot's response during an inadvertent vortex core encounter often exacerbates the effect of the vortex because the induced roll at the edge of the vortex is opposite in direction to that at the center of the vortex.

Because of the complexities of a vortex encounter, a simple parameter, the ratio of the maximum induced rolling moment to the

maximum roll control authority of the aircraft, has generally been used to characterize the wake-vortex hazard (Refs. 45, 111, and 112). Flight-test pilots reported no problem flying at altitude in smoke-marked vortices with induced moments less than 50 percent of the roll control. An analysis of current separation standards in conjunction with preliminary vortex decay data led to a hazard threshold on induced roll of 40 percent of the roll control (Ref. 45). The analysis of wake vortex velocity profiles to yield vortex hazard has made use of a simple parameter: the average circulation over the wingspan of the encountering aircraft (Refs. 36 and 45). Calculations of induced rolling moments have shown that this procedure is justified (Ref. 112).

5. GAPS IN OUR KNOWLEDGE

The FAA wake vortex program has emphasized the collection of data on vortex behavior near the ground and the development of a system to reduce interarrival aircraft separations while maintaining or increasing the level of safety. Vortex behavior is a stochastic process, thus data collection projects necessarily must consider many aircraft (both in number and in type) and many meteorological conditions. Because data collection consumes a large portion of program resources, there are several areas of vortex behavior which have either not yet been addressed, or have too little data to permit definitive conclusions.

An often asked question is, why do we need to collect more data when the vortices from over 70,000 landing aircraft were studied in the 1970's? There are four answers to this question. First, vortex sensors had to be developed and tested at an airport. The testing revealed the suitability of the sensors for vortex data collection and pointed out their limitations. Some systems were tested and set aside (PAVSS, DAVSS, pressure, ultraviolet) because of hardware difficulties or because it was found that the sensor responded to a vortex characteristic that could not be directly related to hazard.

Second, much has been learned about how vortices move in the vicinity of a runway, but only limited data have been reported on vortex decay. The primary reason was the inordinate effort required to collect, reduce, and analyze the vortex strength data. New systems planned for airport tests will significantly simplify the data collection, reduction, and analysis.

Third, as noted above, much has been learned about how vortices move in the vicinity of a runway, but only limited data have been collected on time-of-day effects and how far and with what strength vortices can translate. Such information is paramount for setting vortex standards for parallel and intersecting runways.

Fourth, as vortex modeling improved, it was found that new and more complete meteorological data must be collected (turbulence, atmospheric stability, etc.). To verify the models, the vortex behavior data must be collected along with the more complete meteorological data.

The discussion below focuses on areas where more work is needed. The areas include vortex behavior under various meteorological conditions and quantifying the vortex hazard.

5.1 LONG-DISTANCE VORTEX TRANSPORT

The behavior of vortices transporting over long distances is an important consideration in the operation of parallel and intersecting runways. Many airports (LAX, DEN, SFO, SEA, etc.) have parallel runways separated by less than the minimum (2500 feet) now required for operation as independent VFR runways when considering the wake-vortex hazard. A relatively small amount of landing vortex data was collected at the JFK test site with anemometer baselines extending out to 2500 feet. Systems deployed at Toronto International Airport (Ref. 38) and O'Hare International Airport (takeoff vortices) utilized anemometer sensors out to 1600 and 2000 feet, respectively. A preliminary analysis of the landing data indicates that the current separation standard for runway independence may be reduced, and that guidelines can be formulated for the safe operation of closely spaced parallel runways with displaced thresholds. An increase in the size of the data base and further justification through analytic modeling are required before changes to the present operational procedures could be supported. The strength of the vortices that have transported over long distances near the ground must be measured; at O'Hare the strengths of vortices from landing aircraft were measured out to 1000 feet (unpublished), but more data and greater distances must be examined.

5.2 DEPARTURE VORTICES

The virtual assurance that vortices from a landing aircraft will descend out of the path of a following aircraft (at altitudes greater than about 200 feet) can not be assumed on takeoff --- first because there is generally a headwind blowing the vortex pair back toward the following aircraft, and second because the lead aircraft may be climbing more steeply than the following aircraft. On the other hand, since both aircraft are less likely to be very close to the runway centerline, an encounter may be less probable.

Tests conducted at Toronto International Airport demonstrated the feasibility of detecting and tracking the vortices of aircraft taking off. However, these tests were limited in the volume and types of aircraft observed. The limited amount of data did show that vortices from departing aircraft appear to decay more slowly and to transport over longer distances than vortices from landing aircraft. A test facility for tracking vortices of departing aircraft was subsequently set up at Chicago's O'Hare International Airport. The strengths of takeoff vortices were measured out to 1300 feet. Two goals of these tests were to provide data to determine the necessity of the presently mandated 2-minute hold behind departing Heavy aircraft, and to develop the departure equivalent of the arrival VAS. The tests were completed in November 1980 and most of the data were analyzed, but the FAA vortex program was terminated before the analysis could be

completed and the results published.

5.3 HIGH-ALTITUDE VORTEX BEHAVIOR

Vortex behavior has been studied extensively only in the realm of the planetary boundary layer, particularly when the vortices were in ground effect (less than 200 feet above the ground). This is because the sensors developed to collect vortex behavior data have limited range (about 800 feet). At the higher altitudes the data are sparse or nonexistent. The data consist of approximately 5000 LDV-tracked vortices when the aircraft were about 600 feet above the ground (Ref. 35), and the tracking of smoke-marked vortices during various NASA/FAA flight tests of vortex alleviation techniques (Refs. 86 and 96) and the two-segment approach (Ref. 97). But, such flight tests are usually limited in both quantity and quality of information that can be extracted because of the vagaries of atmospheric conditions. It has been shown (Ref. 109) that the stability of, and turbulence in, the atmosphere are responsible for some of the wide variation in the flight test results.

As noted earlier, vortex behavior is a stochastic process. Limited data can indicate trends in the behavior, but cannot delineate the extremes. The Airman's Information Manual notes that vortices tend to level off about 800 to 900 feet below the generating aircraft's flight path. The distances are known to be related to the atmospheric conditions, but the details have not been quantified. Similarly, the descent rates are known to start out at about 300 to 500 feet per minute, but the details of the slowing down of the descent rate are sketchy; the vertical motion is influenced by buoyancy, turbulence, vortex decay rate, and the continued random action of vertical air currents.

However, knowing vortex behavior in the region between the middle and outer markers and at the vectoring area altitudes can be important. Various traffic merging schemes for more efficient delivery of aircraft to the runway, as well as the multiple approach paths permitted by the MLS, are dependent on and can be affected by vortex motion. Vortices certainly translate with the wind; the descent distances and rates and the decay rates are the unknowns more than 1000 feet above the ground, but it is known that these parameters are directly related to the ambient meteorological conditions. Thus, vortex and meteorological data need to be collected at these higher altitudes (outside the middle marker).

5.4 QUANTITATIVE HAZARD DEFINITION

Our present understanding of the wake vortex hazard is not adequate to assess within a factor of two the strength of a vortex which can be encountered with acceptable consequences. Therefore,

an improved understanding of what constitutes a hazard is required to allow the available data on vortex strength to be interpreted in terms of hazard exposure. The acceptable encounter strength depends upon the phase of flight (landing, takeoff, enroute), the type of encountering aircraft, the aircraft altitude, and the mode of piloting (autopilot, visual, instrument, etc.). Such information could be obtained from simulated encounters with real vortices using a full six-degree-of-freedom encounter simulation. Previous simulator work has suffered from poor definition of the final results desired. The desired results of the simulator program would be twofold: 1) the acceptable limits of a vortex encounter under the conditions listed above, and 2) the maximum strength vortex which will not lead to unacceptable encounters.

The use of maximum induced rolling moment as a vortex hazard criterion has not been totally justified. The rolling moment is dominated by the strength of a vortex and is little affected by the velocities in the vortex core. High core velocities may produce different hazards such as a rapid yaw when the rudder penetrates a core, flameout when a vortex is ingested into an engine, or structural damage.

Another way of looking at quantitative hazard definition is the assessment of how the wake-vortex hazard depends upon phase of flight, type of generating aircraft, aircraft parameters (weight, airspeed, etc.), and meteorological parameters (turbulence, stability, etc.). The additional contribution of wingspan, spanload distribution, and engine placement to hazard decay would be particularly useful to understand. The current classification of aircraft considers maximum certificated gross takeoff weight as the sole determinant of wake vortex hazard. Requisite data exist to assess the contributions of the various factors; detailed analyses might lead to a reclassification of aircraft for purposes of wake-vortex separation.

5.5 OTHER AIRCRAFT

As a consequence of deregulation, a rapid growth in the number of commuter/air-taxi aircraft has occurred. These aircraft are typically in the low-weight range of the Large category. Up to now, relatively few of these aircraft have operated into the high-density terminals. With the increase in number, the exposure of these aircraft to operations behind Heavy and especially behind high-weight Large aircraft is increased and could lead to potential vortex-related problems. Because of the extent of the Large category, the highest hazard probability under the current separation standards occurs with a low-weight Large aircraft (barely more than 12,500 pounds maximum certificated takeoff weight) behind a high-weight Large aircraft barely less than 300,000 pounds maximum certificated takeoff weight). The operational implication is a possible reclassification of the low-

weight Large commuter/air-taxi aircraft for vortex purposes.

Through ICAO, many countries have adopted the separation criteria used by the FAA. There are a number of Heavy and Large aircraft for which little vortex behavior data exist (A-300, IL-62, Concorde, VC-10, Tridents, F-28, etc). Additionally, there are a number of new aircraft types for which no vortex data exists (B-747-400, B-757, B-767, A-310, A-320, IL-76, AN-225). Although some of these aircraft types are rare in the US, US flag carriers operate behind these aircraft throughout the world and the adequacy of the standards can only be inferred. Originally, Great Britain classified the A-300B as Large for wake vortex separation purposes, but in September 1977 it was moved into the Heavy group (the US has always classified the A-300B as a Heavy). Great Britian is considering moving the B-757 (a Large aircraft) into the Heavy group due to the number of vortex incidents recorded behind the B-757.

6. VORTEX AVOIDANCE SYSTEMS

To formulate system concepts for wake-vortex avoidance, one begins by defining the system users, the user requirements, and the operational requirements. The users can be divided into three groups: airports, aircraft, and air traffic control. The user interests and needs are diverse. Airports require a decrease in delays with a possible increase in capacity, maintaining or increasing the safety of operations, minimization of system acquisition and operating costs, and site-independent system performance. For aircraft the needs are to maintain or improve safety of operations, operate during all weather conditions, cover all aircraft, have a low/no cost to acquire/use the system, and improve economics of operation. The ATC must maintain or improve safety of operations, optimize the use of airspace and runways (reduce delays), and have no excess demands on controllers or other factors which might interfere with or degrade other ATC functions.

Based on user needs, a wake-vortex avoidance system must meet the following set of requirements: replace fixed separation standards with adaptive separation standards to maximize traffic flow; detect presence (or guaranteed absence) of vortex hazard and generate information necessary to avoid the hazard (or take advantage of its absence); use a modular system design tailoring the system capabilities and cost to an airport's or aircraft's requirements; ensure uniform system performance independent of environmental or site constraints; design system for maximum independence from ATC systems; and minimize burden on air traffic controllers and pilots. A series of vortex avoidance systems of increasing complexity and cost can be envisioned, starting with the present IFR system using conservative and inviolate separation standards. Ground-based systems have been proposed varying from the simple VAS to a fully automated wake-vortex avoidance system. Airborne solutions to the vortex problem have been examined from the standpoint of using onboard sensors for vortex detection and avoidance, and from the goal of alleviating the vortex hazard via modifications to the vortex-generating aircraft.

6.1 SEPARATION STANDARDS

The FAA now operates two vortex-avoidance methodologies, one for VFR operations and one for IFR operations. During VFR operations the pilot assumes the responsibility for maintaining a safe separation. In normal operations, VFR pilots tend to use closer spacings than those mandated for IFR. Under VFR conditions the pilot apparently feels confident in reacting quickly to any problem which may develop, whether it be a problem on the runway or an encounter with a wake vortex. The VFR pilot also employs various vortex-avoidance procedures such as flying above the flight path and landing beyond the touchdown point of a preceding larger

aircraft. VFR pilots experience occasional vortex encounters which apparently cause them little concern for safety. The observed safety of VFR operations at reduced separations (compared to IFR requirements) is a consequence of the conservatism of the separation standards, pilot training in vortex avoidance, and the improved pilot response to a limited encounter under VFR conditions.

During IFR operations the air traffic controller is responsible for the safe and expeditious flow of traffic and accomplishes this through the sequencing of traffic and ensuring that the appropriate interaircraft separations are maintained. Thus, an additional margin of safety is maintained by the air traffic controllers during IFR operations (to allow for communication delays and possible inaccuracies in assigning and maintaining radar separations).

6.2 GROUND-BASED VORTEX AVOIDANCE SYSTEMS

The VAS was proposed as a first step in a hierarchy of systems. The VAS indicates to controllers when the separation standards could be reduced to three nautical miles regardless of the leader or follower aircraft type. The concept evolved from the analysis of tens of thousands of vortex tracks and the correlation of vortex behavior with the ambient winds. It was noted that whenever the surface wind exceeded a defined criterion, IFR interarrival spacings could be safely reduced to the pre-1970 uniform 3 nautical miles; whenever the surface wind did not exceed the criterion, vortex behavior was unpredictable and the present separation standards should remain unchanged. The criterion is very conservative as it demands that no vortex, no matter how weak or strong (i.e., just GWVSS detectable), be within 150 feet of the extended runway centerline at or inside the middle marker location. The VAS consists of a meteorological tower emplaced near the middle marker of each ILS-equipped runway (precision approaches are required when using reduced separations); electronics and standard FAA cables to transmit the wind data to a central facility (control tower); a microprocessor to average the data, compare the data with the wind criterion, and detect equipment failures; and a display for the controllers. The display presents the averaged wind direction and magnitude and an indication (a green light) when decreased separations may be used.

A fundamental result of queuing theory is that, when a system is operating at or near capacity, a small increase in capacity, which would otherwise appear to be insignificant, can translate into a large decrease in delay. The VAS has been referred to at various times as either a capacity increasing system or as a delay reducing system. It is really both, but fundamentally should be considered as an interim technique to help minimize delays. One should not schedule more aircraft into O'Hare based on a successful

VAS as one cannot always count on having meteorological conditions proper for using uniform three-nautical-mile spacings.

The next entry in the hierarchy of vortex systems (Ref. 26) incorporates real-time vortex tracking to monitor the critical approach region and to provide the pilot with information on corridor status (i.e., is the corridor clear of vortices). A vortex sensor or sensor system is used to monitor the corridor. Vortex position information could be displayed to the controller, or to a pilot via a data link or by lights installed near the runway threshold. A real-time vortex tracking system could be used alone or in combination with a VAS.

A Wake Vortex Warning System represents the ultimate system in the hierarchy of vortex systems and incorporates both the VAS and active real-time vortex tracking, but adds predictive capability to provide adaptive separations (Refs. 26 and 98). The Wake Vortex Warning System achieves greater utilization of the airport by the replacement of fixed, conservative separation standards with an adaptive standard permitting maximum traffic flow. This system might allow operations below 3 nautical miles (vortex behavior data indicate that 2-nautical-mile separations could be used about 90 percent of the time), providing the air traffic control system and the airport complex can handle the increased number of aircraft operations.

6.3 AIRCRAFT-BASED SYSTEMS

6.3.1 Alleviation

The goal of the vortex alleviation effort, conducted primarily by NASA, is to modify the generating aircraft in such a way that the wake vortex hazard is reduced or eliminated at normal aircraft separations. Since the wake vortex is a consequence of the lift generated by the wing, it is not possible to reduce the initial strength. Instead, the approach has been to redistribute the shed vorticity of the wing into the largest possible area and to enhance the decay of the vortex or to cause the two vortices to interact causing mutual momentum cancellation. A wide variety of devices and techniques have been tested in wind tunnels and in full-scale flight tests. The most successful static configurations have been able to reduce the induced-rolling moment from a jumbo-jet vortex to the roll-control level of a small aircraft at three nautical miles. One dynamic configuration (rapid roll inputs with spoilers deployed) showed a reduction of induced-rolling moment to half the roll control level. Unfortunately, the weight and drag penalties were excessive and passengers would find the ride uncomfortable. There is currently only modest detailed understanding about how the various alleviation configurations produce their results.

A successful alleviation system must satisfy three requirements. First, it must be proven to reduce the wake vortex hazard to safe limits at the desired minimum aircraft separation under all desired weather and flight conditions. Second, it must have some method of ensuring that the configuration is activated during actual operations. Third, the costs in weight, drag, and dollars of installing and operating the system must be commensurate with the benefits of the system. From a purely safety standpoint, the costs of such a system may be hard to rationalize inasmuch as the aircraft which bears the cost is not the aircraft which garners the benefits. (Under the hub concept, most aircraft are from the same airline, so there is some justification.) However, the capacity gains (delay minimizations) for commercial aircraft will be the touchstone for justifying any wake vortex system.

6.3.2 Airborne Vortex Sensors

An alternative to the ground-based predictive sensor system involves the aircraft and crew as active participants. The aircraft could be equipped with a real-time vortex sensor which could be either active or passive. If active, it could be monostatic (single sensor located on the aircraft) or bistatic (transmitter located on the ground with the receiver in the aircraft). If passive, it might measure lateral or angular displacement, velocity or acceleration, differential angle of attack, or other phenomena. The sensor would provide information about the vortex location and relative strength and the pilot would be responsible for avoiding the hazard.

As noted in Section 3.2, the airborne-sensor problem is not easy to solve inasmuch as radiation sensors would be looking predominantly along the vortex axis where there is little or no radial velocity component. The sensor system would either have to scan or have a wide field of view as vortices may drift into range from the side or from slightly above or below the flight path. Thus, an airborne sensor really operates only as a safety device to warn the pilot of a possible vortex encounter. Such sensor systems do not obviate the need for a predictive component to schedule reduced interaircraft separations. Use of an airborne vortex sensor system near the ground may be problematical due to ground clutter and the many activities that pilots must attend to during final approach and touchdown. Thus, a ground-based system would still be required to forecast periods when reduced separations may be used and so inform the air traffic controllers so they may sequence the aircraft with reduced separations.

The feasibility and development of an airborne sensor are highly dependent on defining a workable set of requirements (Refs. 99 and 100). The pilot wants to detect a hazardous vortex reliably, and quickly enough to respond, but not so far in advance as to see the wake of the preceding aircraft when it is not a hazard. He also does not want a high false-alarm rate due to

detection of nonhazardous vortices or wind gusts. The hazard potential along the flight path may vary by such factors as phase of the flight, aircraft type, weather, etc.

There are two subtle problems with the airborne-sensor concept. First, the pilot may be provided with too much information which may not be fully understood. Presently, the pilot of the following aircraft knows that the jumbo jet in front of him has left a vortex in its wake. Unable to observe the vortex visually, the pilot realizes from experience that his aircraft should not intercept this vortex if he is maintaining the required safe separation distance and/or if he is above the track of the preceding aircraft. He does not know by how much, in time or space, he has missed the vortex, and he doesn't care. If, on the other hand, the actual vortex location were displayed to him, he might become reluctant to continue his flight toward what looks like an encounter. In the extremely busy final landing phase of the flight, the pilot should not be required to add an unnecessary monitoring task. Second, since any airborne sensor would probably be an expensive piece of equipment, the General Aviation aircraft that need it most probably would not be able to justify the cost.

7. MAJOR ISSUES

A number of important issues surfaced during the operational implementation phase of the VAS at O'Hare. These issues imposed unanticipated requirements on the VAS, and these same requirements will likely be imposed on any vortex system.

7.1 BASIC SYSTEM REQUIREMENTS

During the vortex data-collection activities, an effort began to formulate the system concepts described in the preceding section. The fundamental system objectives based on user needs were obtained, but it was extremely difficult to get the users to define (either formally or informally) the operational requirements for a vortex system. What should the separation standard be in the absence of wake-vortex hazard: three, two and one-half, two nautical miles, or less? Should there be an interim system or should the work be directed toward the ultimate Warning System? Shall the system be operated in IFR only or will the system need to operate under both VMC and IMC conditions? What are the coverage requirements; that is, must the system monitor vortices in the vectoring area, etc? To identify these basic system requirements, a strawman system was proposed. The system would be very conservative, but would allow the vortex separation standards to return to the pre-1970 IFR standard of a uniform 3 nautical miles --- the VAS. However, most of the needed operational requirements were unavailable until the strawman system was ready for commissioning as a demonstration system. During the final stages of the implementation phase, the basic requirements finally began to become clear as many of these operational requirements became constraints. Thus, it was the act of attempting to bring the VAS into the ATC system that elucidated the fundamental operational needs. The major issues confronted by the VAS were the coverage, the concern about missed approaches, the IFR/VFR question, and the inferential or predictive nature of the system.

7.2 VAS COVERAGE

Virtually all the vortex-tracking data have been recorded in the middle-marker-to-runway-threshold region. The VAS evolved from the study of these data; the VAS indicates when this region is clear of vortices. Although some gains may be realized if only this region is permitted to use the reduced separation standards, the utility of the VAS increases if the protected region is extended to the outer marker or beyond.

A detailed analysis was done of the relative safety of reduced separations out to the outer marker when the VAS indicated that reduced separations would be permitted near the runway (Ref. 45).

It was shown that the use of two guidelines maintained the level of risk with VAS-reduced spacings at, or below, the risk using the present separation standards. The two guidelines are: (1) reduced separations of 3 nautical miles are to be used only when the VAS indicates that conditions permit such separations, and (2) precision approaches are required (i.e., no short finals or VOR/localizer approaches). The FAA/TSC LDV was used to gather appropriate winds aloft and vortex behavior data in the middle-marker-to-outer-marker region; the data verified the detailed analysis (Ref. 35) to the effect that the VAS coverage extended from the runway to the outer-marker region. A limited flight test was conducted at O'Hare during which an FAA Gulfstream was intentionally vectored close behind landing Heavy aircraft. Approaches with separations as low as 2 nautical miles were safely flown. Two vortex encounters were experienced; however, they occurred when the guidelines above were not followed. The first encounter occurred with the Gulfstream 50 seconds behind an L-1011 approximately 6 miles from touchdown; however, the Gulfstream was more than 3 dots below the glideslope and less than 2 miles behind the L-1011. The second encounter occurred just inside the middle marker behind a B-747; however, the Gulfstream was 38 seconds or only about 1.5 nautical miles behind the B-747.

The uniform three-nautical-mile separations would be permitted using the VAS only after the lead aircraft is inside the outer marker location. In most situations the aircraft are in trail using the terminal area standards prior to crossing the outer marker. VAS-reduced separations will be due to the combination of the natural closing which takes place as the lead aircraft slows to its final landing speed (the accordion effect) and the lack of the need of an approximately 0.5-nautical-mile buffer now used by controllers to ensure that requisite separations are maintained at runway threshold. Although three nautical miles is claimed to be safe using the VAS, the interarrival separations behind Heavy aircraft will most likely initially be decreased by only the 0.5-nautical-mile buffer. To take full advantage of the capability of the VAS (3 nautical mile spacings), the terminal area separations would need to be reduced outside the Outer Marker (see Section 8.4).

7.3 MISSED APPROACHES

Proposed ATC procedures for the VAS required that an aircraft at VAS separations behind a Heavy aircraft must execute a go-around if the Heavy aircraft goes around (a rare situation) at, say, the middle marker. Concern was expressed that the double go-around would create an unsafe situation. However, analysis has shown that the flight profiles of the trailing aircraft can be maintained above the profiles of the lead aircraft as long as the trailing aircraft executes a go-around no closer than 1.25 nautical miles from the middle marker. This procedure avoids any vortex

problems during the climbout.

7.4 IFR/VFR USAGE OF VAS

The VAS was conceived as an interim measure to minimize delays during IFR operations. If the conditions are such that VAS-reduced separations are not permitted, it has been posited that such information should be provided to the pilots during VFR operations --- the implication otherwise being the withholding of safety information; if reduced separations cannot be used in IFR, the reduced separations inherent in VFR perhaps should not be accepted. When the VAS does not indicate that reduced separations are permitted, it does not mean that such separations are unsafe --- it means that not enough information is available to say that it is absolutely safe. During high-wind conditions, data indicate that vortices are not a problem; during light-wind conditions, data are not conclusive but usually vortices are not a problem. In a sense, these low-wind conditions are when the "Caution Wake Turbulence" advisory has real meaning.

Chicago O'Hare exercises control over aircraft even during visual approaches. With such a high density of aircraft, it is imperative for the O'Hare controllers to follow the progress of all aircraft be it VMC or IMC. Thus, separations in VMC are not too different from separations in IMC at O'Hare (the difference being, perhaps, just the 0.5-nautical-mile buffer discussed in Section 7.2). Benefits from the VAS are derived in IFR, but one must consider the potential adverse implications of VAS on VFR operations. It should be noted that O'Hare achieves its greatest capacity increase in VMC by using triple approaches. A cost-benefit analysis of the VAS at O'Hare (Ref. 101) found that, given the present effectivity (percentage of the time the VAS indicates reduced separations are allowed) more than 40 percent of the pilots must request additional separation under VMC conditions when using two runways for approaches to drive the cost of the VAS operation above the IFR benefits. As will be discussed in the next section, one alternative would be to increase the effectivity of the VAS enough to offset any losses in VFR.

7.5 PREDICTIVE/INFERENTIAL NATURE OF VAS

Based on the study of vortex behavior from tens of thousands of aircraft, the VAS algorithm was developed. It was found that under certain wind conditions vortices posed no threat to any aircraft three nautical miles behind the vortex-generating aircraft. By measuring the wind in the vicinity of the runway, one can "predict" when separations can be set at a uniform three nautical miles. Since the vortices are not directly measured, the system is also inferential. Some section of the aviation community questioned the viability of predictive/inferential information in

place of real-time measurements of the vortices.

Although it is generally true that a primary measurement of the phenomenon is desirable, there are precedents for predictive and/or inferential systems. The current vortex avoidance separation standards are accepted as a baseline safe system, but are essentially predictive in nature (no hazard when using 3, 4, 5, and 6 nautical miles; the VAS assumes no vortices/problems when using 3 nautical miles during certain wind conditions). Other aviation information also depend on prediction/inference. Winds measured sometimes a mile or two away from the landing runway are presumed to be valid on the runway. RVR is measured over a short horizontal path and is used to describe the slant visual range conditions that a pilot should expect.

The VAS and other sensor-based vortex avoidance systems rely to some extent on predicting vortex behavior on the basis of meteorological measurements, rather than just direct measurements of wake vortices themselves. The lead time required to set up aircraft spacing on final approach requires prediction of vortex behavior. The advantage of using meteorological parameters to predict vortex behavior is that they can always be measured.

8. OPTIONS/STRATEGIES

The preceding sections outlined what is and what is not known about aircraft wake vortices and some of the implementation problems/constraints that must be addressed. In this Section various alternative options or strategies are proffered. The alternatives, not necessarily mutually exclusive, include (1) halting all research and development on wake vortices, (2) resurrecting VAS and assessing total system operational requirements for acceptable vortex solutions, (3) substantially increasing the effectiveness of the VAS and thereby mitigating the VFR issue, (4) formulating the requirements for ground-based and airborne sensor systems thus moving toward systems more advanced than VAS, (5) continuing the search for effective alleviation of the vortex hazard, and (6) re-examining procedures in the light of vortex behavior to expedite traffic flow. Each option is briefly described along with its pros and cons, the risks and problems to be expected, and an outline of the work to be done. An effective wake vortex program should consist of some combination of these alternatives with proper emphasis consistent with FAA priorities and goals.

At this time there are six areas that appear to require further vortex research and development: parallel runways (including intersecting runways and staggered thresholds), reclassification and revised separation standards, further understanding of vortex behavior under various meteorological conditions, sensor development, hazard definition, and alleviation. Further data collection is warranted in these areas, but detailed planning is needed to demonstrate why more data are needed, how the results would be used, how the data should be collected, how many aircraft and types are required, etc.

8.1 HALT RESEARCH AND DEVELOPMENT ON WAKE VORTICES

One program option is to cease research and development on wake vortices. Safety is probably not an issue as long as the current separation standards are maintained. The FAA would save resources on the wake vortex program as well as on a number of other capacity-related programs. This was the course selected by the FAA in 1982.

However, the outlook is grim concerning the capabilities of the high-traffic-density airports to meet forecasted demand and to respond effectively to costly delays. The growth of aviation at the busy airports would need to be curtailed by restrictions on the number of operations. Construction of additional runways and airports would become the primary means to foster the expansion of aviation. Alternatives also include abandoning the "first-come, first-served" philosophy and the segregation of aircraft both

spatially (dedicated runways for specific aircraft categories and diversion of some traffic to less congested airports) and temporally (mandatory scheduling to avoid peaks in demand). Safety might become an issue in VFR as the air traffic control system contends with the increasing mix of commuter-sized aircraft with the Heavy and heavier Large aircraft.

8.2 RESURRECT VAS

Another option would be to resurrect the effort on the VAS. The VAS previously was unacceptable primarily due to procedural problems. The exercise was worthwhile as vortex behavior knowledge was significantly expanded and the requirements for effective solutions to the wake vortex problem are becoming clear. Thus, a program option would be to resurrect VAS first by elucidating the requirements for acceptable vortex solutions and then by planning the research needed to translate these requirements into effective solutions.

The requirements can be divided into three types --- basic, procedural, and systems. The basic requirements are those which affect any concept to mitigate the problem of wake vortices. Examples of such basic requirements are the use of the concept in VMC and IMC, the impact on the ATC system (mandatory go-arounds, precision approaches, effect of controller blunders, etc.), and the minimum separation standards. Procedural requirements are those imposed when translating the results of extensive data collection efforts into revised ATC procedures. Primary examples are the possible reclassification of aircraft based on vortex behavior and the use of parallel or intersecting or staggered runways. How much of a specific type of data are required, in what form they should be presented, and what other rules or procedures that bear upon the procedure under review must also be examined. System requirements are those which pertain to the design of any ground-based or airborne (including alleviation) system. Examples of system requirements are the coverage or region monitored, criteria for certification, interfaces with other ATC equipment, etc. As indicated by the experience with VAS, it is imperative to formulate the requirements with the appropriate agency and user organizations before pursuing any specific development effort.

It has been suggested by some members of the aviation community that a VAS based on a pure crosswind criterion would be more acceptable than the proposed wind algorithm. It was felt that pilots and controllers could more easily relate to something with which they are more familiar, since most of the previous literature (AIM, controller's handbook, etc.) discuss the possibility of a vortex hazard in terms of the magnitude of the crosswind. This conversion is trivial to implement technically as it would require only a relatively minor modification to the system software with no hardware changes. But, first, there would be a measurable drop

in the effectiveness of the VAS using a crosswind criterion since more area would be taken from the green region where reduced separations are allowed. Second, there is the undesirable implication that crosswind runways would be preferred to runways with headwinds since the crosswind runway would offer reduced interarrival separations.

Although 3-nautical-mile separations are claimed to be safe using the VAS, in reality initially the separations would be closer to 3, 3.5, 4.5, and 5.5 nautical miles rather than 3, 4, 5, and 6 nautical miles, respectively. This is attributed to no longer needing the 0.5-nautical-mile buffer used by air traffic control to maintain the separation standards at runway threshold (Section 7.2). Perhaps VAS would be more palatable if it were introduced as a system affecting only the separation of Large and Small aircraft following Heavy aircraft (VAS-reduced minimum separation of four nautical miles for these aircraft pairs). Once operational experience is gained using this approach, a reduction to a three-nautical-mile minimum standard could be pursued. Such a course of action was suggested by ALPA representatives.

8.3 ENHANCED VAS

The ATC system is capable of accommodating three-nautical-mile spacings for controlling arrival aircraft during IMC. Because of possible hazardous vortex encounters, the separation standards are increased for certain leader/follower aircraft pairs. This increase in separation is highly conservative since the actual wake vortex hazard is significant for only a small fraction of the time. Under most conditions the vortices will have dissipated or drifted out of the approach flight path before the arrival of a following aircraft at a three-nautical-mile spacing.

A system developed to reduce the impact of the very conservative separation standards is the VAS. The VAS identifies wind conditions when wake vortices were never observed to linger in the path of a following aircraft at a three-nautical-mile separation for over 70,000 landings. The VAS is also very conservative in that the detection threshold for the sensor used to collect the data (GWVSS) is considerably below the vortex hazard threshold. The VAS does not exhibit high effectiveness (i.e., the fraction of the time that three-nautical-mile separations may be employed is smaller than necessary; Ref. 106) since wind measurements alone do not accurately predict all the times when vortices are not a problem. The VAS would allow 3-nautical-mile spacings on the order of 20 percent of the time, while there is no vortex problem 99 percent of the time behind a B-747 at a three-nautical-mile separation. This is because the VAS uses a wind criterion only, and an extremely conservative one at that, while vortex behavior is dependent on a number of additional parameters.

The low effectiveness of the VAS contrasts markedly with the successful use of VMC to deal with the wake-vortex problem. Since the use of VAS solely in IFR conditions has introduced problems, it appears that part of the cost of introducing the VAS to decrease IFR delays is the loss of VFR capacity obtained by operating below the IFR and vortex separation standards. The culprit in this scenario is the poor effectiveness of the VAS. The VAS effectiveness could be significantly improved by (1) using a more realistic hazard threshold, (2) finding additional predictors of vortex behavior (such as atmospheric stability and/or turbulence criteria) to supplement simple wind measurements, and (3) including vortex sensors for real-time updates of vortex behavior. These three improvements might be taken singly or in combination to substantially increase the VAS effectiveness. If such an improved VAS could justify the reduced separations in VMC, it could be capable of increasing overall capacity at the major hub airports.

The risks entailed with this option are twofold: First, some of the present procedural problems with the acceptance of the VAS will need to be addressed, such as the double missed approach. Second, research is required to identify the specific enhancements; the limited effort to date indicates that it is probable that enhancements can be made, but the ultimate effectiveness of the system is unknown. The tasks will involve collecting and analyzing data on the correlation of atmospheric stability and turbulence with vortex behavior, and a detailed study of all long-lived vortices. Once a technique or techniques are identified, further data collection may be required to satisfy the user community.

8.4 GROUND-BASED SYSTEMS

The hierarchy of systems (VAS, enhanced VAS, vortex tracking, Wake Vortex Warning System) offers flexibility in implementation and development as each more complex system builds on the use of the less complex system(s). Based on current needs and near term projections, about 20 to 30 airports in the US could benefit with a VAS and about 6 of these airports could employ the benefits of a full Wake Vortex Warning System. The capacity/delay-savings involved are extensive. Expected delay savings for 1985 to 1995 at the top 20 airports, using FAA-projected demands, are $1.25 billion (1976 dollars) for a 40-percent effectiveness VAS versus today's standards, and an additional $4 billion for a 60-percent effectiveness VAS operating with a 2.5-nautical-mile standard (Ref. 107).

For systems more advanced than the VAS, a vortex tracking/measuring system is required. Developments with the GWVSS hold considerable promise for such a system in the middle marker to runway threshold region. If vortex coverage is required when aircraft are at higher altitudes (to the outer marker, say), then much work remains to test and develop such a sensor system (e.g.,

various forms of lidar or radar). At the present time, it appears that the terminal-area standards beyond the outer marker will need to be reduced to achieve less than three-nautical-mile separations at the runway threshold. The need, however, for a complex sensor system has not been firmly established, nor have the operational requirements and limitations been identified. The next logical step would be to formulate these requirements, determine whether sensors can be incorporated into an advanced vortex avoidance system, develop such sensors, and determine how such a vortex avoidance system would operate in the air traffic control system.

Combining the VAS with a real-time vortex tracking system would meet some of the objections raised by the aviation community concerning use of the VAS alone. Such a system with real-time tracking of vortices would increase the effectiveness of the VAS and be used both in IFR and VFR. Sufficient data exist to determine the viability of this concept, the technical risk being the ability to develop the sensor and the attendant data processing algorithms for real-time application. If the real-time vortex tracking system can be coupled with the results of VAS enhancement, the effectiveness should be better than 90 percent in both IFR and VFR.

8.5 AIRBORNE SENSOR SYSTEMS

The feasibility of using an airborne sensor for detecting vortices needs to be investigated, with emphasis in two major areas. First, a review of some of the more recent advancements in sensing techniques should be conducted; there have been many developments in the infrared, visible, and microwave regions, as well as accelerometers and gyroscopes, which could be applied to sensor development. Second, a set of operational requirements needs to be defined which should allow the determination if a useful sensor can be developed, while at the same time providing a reliable detection of a possible vortex hazard. The variability and unpredictability of aircraft flight paths make the precise definition of sensor requirements somewhat difficult. However, in order to be useful in a vortex avoidance system concept, there are a number of definitive sensor requirements that must be met.

The major risk of the system is that the sensor and how it would be used are both unknowns. If this option has merit, a detailed requirements study should be undertaken. Based on the requirements, system concepts can be defined and evaluated, and a demonstration sensor system designed, built, and tested. Part of the evaluation phase should include the feasibility of the system as perceived by the aviation community in light of the probability and range of detection and the false-alarm rate. However, as noted in Section 6.3.2, both a ground-based and an airborne sensor approach can be followed as an airborne sensor by itself is not a solution. A VAS, enhanced VAS, or Vortex Warning System will still

be required on the ground so that reduced separations can be forecast and the air traffic controllers can appropriately sequence and position aircraft at the reduced separations.

8.6 ALLEVIATION

The primary goal of the alleviation program is to find a configuration that produces satisfactory alleviation with acceptable costs. The tests to date indicate that static configurations are not likely to be successful; dynamic configurations are more likely to yield satisfactory results. An immediate task is to understand fully past results and suggest new configurations that can be achieved with an acceptable ride, performance (fuel economy, landing speed, etc.), and stress on the generating aircraft. An important support task for the alleviation program is a determination of what constitutes "satisfactory" alleviation. How weak must a vortex be to be considered benign?

The implementation of an alleviation system will require several efforts and should be pursued as a joint NASA/FAA endeavor. First, the criteria for acceptance must be established. Second, the system must be certified as effective and airworthy. The following aircraft must be assured that the alleviation system is operating. Third, the costs associated with the system must be defined. Fourth, an implementation plan must be devised. The incentives for an individual airline to install alleviation are difficult to envision since the benefits apparently accrue to the following rather than the generating aircraft.

8.7 PROCEDURES

One area that has received little attention as a means for increasing/improving the flow of traffic from the standpoint of wake vortices has been the possible use of revised procedures. Much has been learned about vortex behavior, but little of this tremendous increase in knowledge has been applied to establishing new or revised rules for expediting traffic. In the operation of parallel and intersecting runways there are cases (such as offset parallels, etc.) where logical application of basic knowledge of vortex behavior should improve overall efficiency. Simple wind criteria and/or segregation of aircraft could be used to expedite traffic flow. Intersecting runway operations especially may require case-by-case examination to achieve optimal procedures.

8.7.1 Reclassification

The current classification of aircraft into Small, Large, and Heavy is based on the maximum certificated gross takeoff weight, with boundary limits of 12,500 lb and 300,000 lb (not actual weight), respectively, between classes. The same classes are used

to describe both generator and follower aircraft, although the important parameters may be different in the two situations. The most notable feature of the current classes is the extreme range of aircraft size in the Large class. The separation standards are designed to be conservative in that the separation must be safe for all generator-follower pairs under the worst of conditions. The separation standard is therefore nominally set by the two following limiting cases:

(1) The strongest generator and the most susceptible follower in the respective classes, the former at maximum weight, the latter nearly empty; and

(2) The meteorological conditions leading to the longest vortex persistence.

The most obvious and perhaps easiest improvement in the current classification might be obtained by splitting the Large class into two; in the United Kingdom, the present scheme of four classes is similar to the result of such a change.

The goal of reclassification is to optimize the aircraft classes and separation standards for maximum airport capacity subject to the constraints of safety, efficiency, and acceptable complexity. The basic variables of reclassification are the number of size classes and the dividing lines between the classes. Other factors such as wingspan and engine placement may be combined with weight to derive an optimum size parameter. Incorporating the best understanding of wake vortex decay and an improved hazard model into the wake vortex classes and separation standards may produce a significant improvement in airport capacity over the present standards.

8.7.2 Parallel/Intersecting Runways

Many airports were developed with the most often used runways constructed in parallel pairs to maximize traffic flow in peak demand periods. Since, in general, these plans were generated before the advent of the Heavy jets, the lateral separation was dependent mostly on available land and the requirements for radar coverage and ILS navigation procedures. However, the possibility of a vortex from an aircraft operation on one runway transporting across to interfere with an operation on a parallel runway led to the establishment of restrictive procedures when the runways are used for simultaneous operations. When these procedures were developed, very little detailed information on vortex behavior was available and the resultant procedures now seem to be excessively conservative. The various aircraft wake-vortex sensing systems have produced an initial data base on long transport vortex behavior which can be used to develop an initial set of more efficient procedures, but more data (measurements) are required to finalize a standard. Operational procedures for the use of

intersecting runways and intersection departures have similar conservative restrictions. Although these situations must be treated as individual cases, similar data analyses may be used to increase the efficiency of these operations.

9. RECOMMENDED WAKE VORTEX PROGRAM

Many options or strategies were suggested in the previous Section. They range from terminating any further work to the development of a full wake vortex avoidance system. A recommended wake vortex program is sketched below which is a combination of the various options/strategies; the intent is to lay out a complete and logically consistent program building on the extensive efforts of the 1970's by the FAA Technical Center, NASA, and VNTSC. Ten components are identified, many of which are dependent on or derive from other activities. These recommendations are those of the author.

9.1 REVIEW PAST ACTIVITIES

Because of the hiatus in the wake vortex research and development, the past activities must be reviewed and in some cases documented. Reports such as this one are needed to place future data collection activities into proper perspective by concentrating on improved and more complete meteorological information.

9.2 CAPTURE VAS REQUIREMENTS

The exercise of attempting to implement an operational VAS at Chicago O'Hare brought to light many hitherto unexpressed requirements. These requirements should be reviewed, analyzed, and documented as a means for obtaining the aviation community's early approval of the concept of a ground-based system for decreasing interarrival separations of aircraft.

9.3 DEVELOP VORTEX SENSORS

Many sensors have been employed to record vortex motion and decay. An active ground-based vortex sensor will be required in any eventual operational vortex system deployed at an airport. Efforts are needed to develop such a sensor system that can operate unattended, around the clock, and in all weather conditions. The feasibility of an airborne vortex sensor should also be pursued.

9.4 ADDITIONAL DATA COLLECTION

Additional data collection activities are required. Six areas need to be addressed in the data collection:

(1) New aircraft types,
(2) Developing and verifying an enhanced VAS,

(3) Developing and verifying atmospheric (as applied to vortex behavior) forecasting models,
(4) Developing and verifying hazard model(s),
(5) Additional data for reclassification, and
(6) Parallel/intersecting runway standards.

Many new aircraft types are now in use which were not around during the previous data collection programs (B-747-400, A-310, A-320, B-757, B-767, MD-11). Data must be collected on these aircraft for vortex behavior modeling. An enhanced VAS will incorporate new meteorological parameters; data must be collected to develop and verify the algorithms which translate the measurements into vortex separation standards. For any vortex system to be accepted into the airport environment, vortex behavior must be forecasted so that air traffic control can schedule reduced separations well before the aircraft land, as well as deal with impending changes when the system indicates that reduced spacings may not be appropriate at some forecasted time in the future. The hazard model employed directly affects the design of any system as well as any reclassification scheme; data is needed to further refine and verify any proposed new hazard models. Reclassification may in itself lead to gains in capacity, but additional data, particularly on the new aircraft types, must be collected before developing a new matrix for wake-generating and following aircraft separation standards. Finally, data is required to examine the parallel and intersecting runway standards to determine how best to use these runways from a vortex point of view. Initial emphasis should be on landing aircraft, but takeoffs will need to be examined for the same six ares.

In the longer term, more complicated separation schemes involving individual aircraft type, actual weight, configuration, and the like will become feasible, including separation standards specified in fractions of a nautical mile.

9.5 VORTEX MODELING

Models (i.e., computer algorithms) are needed to predict vortex behavior under various meteorological conditions. The efforts begun by Greene (Ref. 109) and others need to be expanded to describe vortex behavior (motion and decay) more completely. In addition, a forecasting model needs to be developed; such a model would incorporate both vortex behavior measurements and meteorological measurements to estimate if and when vortex separations may need to be changed.

9.6 HAZARD DEFINITION

The definition of a vortex hazard is only crudely known. More effort is required as a hazard model is included in vortex systems

(albeit a simple one) and is of paramount importance in reclassification efforts. The better one can describe the hazard, the more efficient the vortex system or classification of aircraft.

9.7 RECLASSIFICATION

The methodology for setting vortex separations needs to be documented for review. The current standards are based on three weight classes. Incorporation of more complete vortex behavior and hazard criteria into the definition of aircraft classes should lead to more efficient groupings of aircraft for vortex separation purposes.

9.8 AIRPORT TEST SITE

An airport test site needs to be established for the long-term data collection activities discussed above. In addition, the test site would become the demonstration airport for an enhanced VAS, real-time vortex tracking system, and/or the Wake Vortex Warning System.

9.9 ALLEVIATION

NASA should be encouraged to continue its efforts in seeking an aerodynamic solution to the wake vortex problem. Such a solution could conceivably be effective for all phases of flight and would be effective at all airports (not just those with a vortex system installed).

9.10 AIRBORNE VORTEX SENSORS

NASA should be encouraged to continue its efforts in finding an airborne vortex-sensing system. Such a system permits the pilot to "see and avoid" wake vortices. Such sensors will increase safety, but, as noted in Section 6.3.2, a ground-based system will still be required to forecast and set up reduced separations in the terminal environment.

9.11 FINAL NOTE

A wake vortex program has been re-established. Capacity problems at the major airports demand that vortex-imposed restrictions be reduced when possible and without compromising safety.

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