NASA Contractor Report 4024

Potential Impacts of Advanced Technologies on the ATC Capacity of High-Density Terminal Areas

Robert W. Simpson, Amedeo R. Odoni,
and Francisco Salas-Roche

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ABSTRACT

Advanced technologies for airborne systems (automatic flight control, flight displays, navigation) and for ground ATC systems (digital communications, improved surveillance and tracking, automated decision-making) create the possibility of advanced ATC operations and procedures which can bring increased capacity for runway systems. A systematic analysis is carried out in this report to identify certain such advanced ATC operations, and then to evaluate the potential benefits accruing over time at typical US high-density airports (Denver and Boston). The study is divided into three parts: Part 1, "A Critical Examination of Factors Which Determine Operational Capacity of Runway Systems at Major Airports", is an intensive review of current US separation criteria and terminal area ATC operations. It identifies 11 new methods to increase the capacity of landings and takeoffs for runway systems; Part 2 - "Development of Risk Based Separation Criteria", is the development of a rational structure for establishing reduced ATC separation criteria which meet a consistent Target Level of Safety using advanced technology and operational procedures; Part 3 - "Estimation of Capacity Benefits from Advanced Terminal Area Operations - Denver and Boston", provides an estimate of the overall annual improvement in runway capacity which might be expected at Denver and Boston from using some of the advanced ATC procedures developed in Part 1. Whereas Boston achieved a substantial 37% increase, Denver only achieved a 4.7% increase in its overall annual capacity.

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LIST OF SYMBOLS

SYMBOL	DEFINITION
A	alert criteria
AFCS	automatic flight control system
aircraft categories:	
A	single-engine prop < 12,500 lbs.
B	twin-engine prop > 12,500 lbs.
C	high-performance/heavy/turbojet, & all others
ASDE	airport surface detection equipment
ASID	automatic standard instrument departure procedure
ATC	air traffic control
$A^1{}_{ij}$	time available to insert one takeoff (seconds)
$A^2{}_{ij}$	time available to insert a second takeoff (seconds)
CA	conflict alert
CCC	capacity coverage chart
D_b	braking distance
D_{Ei}	exit distance for i^{th} exit
D_f	flare distance = 1000 feet
DME	distance measuring equipment
D_t	taxi distance
ELOT	expected landing occupancy time
EMAP	evasive missed approach capability
ETOT	expected takeoff occupancy time
ETTD	estimated time to touch down
fpm	feet per minute
fps	feet per second
H	hazard criteria

HA	hazard alert
ILS	instrument landing system
IMC	instrument meteorological conditions
I^{n}_{ij}	runway idle time between takeoffs when n takeoffs are being inserted
I^{o}_{ij}	idle runway intervals between landings at capacity flow rate (seconds)
$\overline{LCAP}$	average landing capacity
MGTOW	maximum gross takeoff weight: (H) = mgtow $>$ 300,000 lbs. (Heavy) (L) = 12,500 $<$ mgtow $<$ 300,000 lbs. (Large) (S) = mgtow $<$ 12,500 lbs. (Small)
MLS	microwave landing system
MSAW	minimum safe altitude warning
n_{ij}	number of takeoffs inserted in each landing interval
n_{ijmax}	insertion matrix (takeoffs per landing)
NTZ	no transgression zone
OM	outer marker
pdf	probability density function
P_{ij}	probability of occurrence of the pair ij
PMS	performance measurement system
RNAV	area navigation
RUNCAP	airport capacity computer model - 1
RUNSIM	airport capacity computer model - 2
S	separation criteria
S_{cF}	controlled separation criteria for parallel frontal encounters
S_{cO}	controlled separation criteria for parallel overtake encounters
SEPMIN	minimum separation
SEPREL	separation required at release
SID	standard instrument departure procedure

S_m	monitored separation criteria
STAR	standard terminal arrival route
S_u	unmonitored separation criteria
SUPCAP	airport capacity computer model - 3
S_{12}	radar separation
t_b	time for braking
TERPS	terminal instrument procedures
t_f	time for flare
t_i	time for taxi to exit i
t_{ij}	minimum approach intervals for the pair ij (seconds) under IMC
TLS	target level of safety
TRACON	terminal area approach control
V_A, V_F, V_O	aircraft velocities
V_{app}	approach groundspeed
VASI	visual-approach slope indicator
V_{ga}	measured groundspeed on final approach - Kts
V_{ge}	expected taxi speed on runway before exit - Kts
VMC	visual meteorological conditions
VSD	vortex separation display
V_1	decision speed
ΔSE_{12}	spacing error buffer
Δx	along-track separation
Δy	lateral separation between aircraft (nominal separation S_u)

PART 1. A CRITICAL EXAMINATION OF FACTORS WHICH DETERMINE OPERATIONAL CAPACITY OF RUNWAY SYSTEMS AT MAJOR AIRPORTS

1.1 Description of Takeoff and Landing Operations of Transport Aircraft

In this section we will briefly describe current and future operations of aircraft in the takeoff, landing, and approach phases of flight. Our purpose is to understand the operational factors which constrain the introduction of improved ATC procedures.

1.1.1 Takeoff

A critical decision speed exists for every transport aircraft takeoff which depends on weight, temperature, airport altitude, and wind component along the runway direction. At the decision speed, the pilot makes a commitment to takeoff, or to abort. Thus, once the tower controllers see the nose-wheel lift off, they have a commitment that the aircraft will leave the runway even if an engine failure (or other problem) occurs. Before nose-wheel liftoff, the lift on the wings is very small, so that the wake vortex is only generated after that point on the runway. This point is roughly 30 seconds after start of roll, V_1 (decision speed) is roughly 140 kts, and the distance from start of roll is roughly 3500 feet.

The aircraft will accelerate to an initial climb speed and will complete raising its wheels and wing flaps before 400 feet above the airport elevation. At that point the crew will usually engage the autopilot, and is prepared to perform an initial turn from the runway direction under radar vectors from the departure controller, or as prescribed by a SID (Standard Instrument Departure) procedure. A SID prescribes a three-dimensional route from the runway to some departure fix point, which can be flown by all aircraft regardless of their weight, climb performance, or windspeed and direction. There may be noise-preferential SID's where the aircraft is maneuvered to avoid noise-sensitive population areas around the airport. In the future, more complex SID's could be flown by aircraft with advanced AFCS (Automatic Flight Control Systems) to provide lateral and vertical separation between departing aircraft, and even time-longitudinal separations provided by a 4-D SID.

Normally, all jet transport aircraft will use the full length of available runway. Smaller turboprop or piston aircraft may be directed to any suitable runway entry point to begin their takeoff, since they may not require the full length of longer runways. These are called "intersection" takeoffs. Care must be taken to ensure that such mid-runway takeoffs do not encounter the wake vortex of a preceding aircraft. Small aircraft may be vectored away from the runway direction at roughly 200 feet altitude before reaching the end of the runway.

1.1.2 Final Approach and Landing

Depending on weight, runway elevation, and temperature, the crew of each transport aircraft will compute an approach airspeed and a landing distance. There may be a correction for wind gustiness, and the pilot may elect to fly 5-10 knots above the speed if there is an excess of available landing-runway distance. The AFCS may be set to control the selected approach airspeed. Normally, there is a headwind in the landing direction, so that the groundspeed is less than this indicated approach airspeed. In the future, the ground ATC system may wish to know the planned approach airspeed for each aircraft. Today only the pilots know the values of planned approach speed, and they are not asked to transmit this information to ATC.

After descending through 1000 feet above ground, the earth's boundary layer will cause a diminution of the windspeed so that the aircraft's groundspeed may increase over the last three miles of the approach. On the other hand, the pilot may reduce his final approach speed in this region also, since he has made no commitment to maintain speed. The approach glide path is normally between 2.5^{o}-3^{o} for the current ILS (Instrument Landing System) and there are visual-approach slope indicators (VASI) set at the same angle. The glide path crosses the runway threshold at 50 feet, and the touchdown point is roughly 1100 feet from the threshold. Upon touchdown, the wake vortex ceases.

Aircraft can fly at steeper angles up to 5^{o} under visual conditions or with advanced AFCS without difficulty, particularly if they have slower approach speeds. The 3^{o} slope corresponds roughly to a 1/20 gradient so that if the approach ground speed is 120 knots, the vertical speed is 6 knots, or 10 fps, or 600 fpm. This vertical speed is kept at such low values to give pilots time to see the ground, approach lights, and runway in times of poor visibility. With the future MLS (Microwave Landing System), it is possible to consider a two-segment approach with a steeper angle of 6^{o} to an altitude of 600 feet (about 2 n. miles, and 60 seconds from touchdown), which then transitions to a shallower 3^{o} slope. There are wake vortex implications of such an approach procedure.

Upon sighting the runway, the pilots normally switch off the AFCS system to conduct the flare and touchdown. In good weather they may "duck under" the glide slope to touchdown close to the nominal touchdown point, but the flare and subsequent float will normally carry the plane past the nominal touchdown point into the next 1000 feet of runway, depending on their actual airspeed and their control over thrust or power. After touchdown, spoilers will rapidly dump wing lift, and braking and thrust reversal can be initiated. The pilots have discretionary control over the deceleration they desire on a normal dry surface, but may be cautious with wet or icy surfaces. Given visual location of oncoming runway exits, they may control the braking action to "make" the exit, particularly if it saves distance in taxiing to the gate. At night (or in poor visibility) it is difficult to see these exits, and the braking may occur to reduce to taxiing speed on the runway, whence a visual search commences for the next exit. Thus, we can expect longer runway-landing-occupancy times at night or in poor visibility conditions. There are green exit centerline guidance lights imbedded in the runway leading into each exit at some airports today, and improved exit-guidance systems can be conceived for future operations under poor visibility conditions if it proves beneficial.

Using current ILS approach procedures, there is an OM (outer marker) roughly 5 n. miles from touchdown (1500 feet above runway elevation) where the glide path commences. To initiate the final approach, aircraft are vectored onto the centerline at least 2 n. miles beyond this OM at intercept angles of 20-30^{o} so that the AFCS or pilot can acquire and establish tracking. They are controlled vertically to be at the 1500-feet altitude (or equivalent) before or during this intercept maneuver, so that they can then approach the outer marker from below the glide path and already established on the centerline. A visual and aural signal warns the pilot on reaching the outer marker, and they prepare to acquire and track the glide path.

The glide-path indicator also displays the descent of the glide path towards the aircraft, and they may also have RNAV (area navigation) or DME (distance measuring equipment) indications to show the longitudinal distance to outer marker and threshold. All aircraft are constrained to follow this final-approach initiation procedure at major airports when ILS approaches are in operation. Since aircraft have different approach speeds, they spend varying amounts of time on the final glide path. In good visibility, some smaller aircraft may forego the full ILS approach in order to shorten the time to landing.

With a future MLS, there is no need to have an outer marker, and there could be alternate lateral "centerlines" to the runway, and alternate vertical glide paths. Unfortunately, there is a need to transition from ILS operations, and for many years there will be dual ILS/MLS installations and a mix of aircraft using ILS or MLS equipment on the same runway. Approach procedures must be created to accommodate mixed ILS/MLS operations, and approach operations which use RNAV and advanced AFCS. We can conceive of multiple lateral-segment approach procedures to be flown by certain aircraft with advanced AFCS during approach to the runway.

The wake vortices of preceding aircraft are a safety problem throughout the approach procedure. Small aircraft must avoid descending through the wake vortex of heavier aircraft beyond the outer marker, and must avoid getting below the glide path of the previous aircraft on final approach. The critical time is at touchdown where the wake vortex should have dissipated before the small aircraft arrives. It may be efficient to ensure lateral or vertical separation from the wake vortex at earlier stages in the approach to increase landing capacity. We will discuss this later.

All instrument approach procedures are predicated on the assumption that they will continue into a Missed-Approach Procedure if the pilot elects to abort. While not a common occurrence, the traffic procedures must allow for such a possibility for every aircraft. The pilot will apply full power, initiate a climb, clean up the gear and flaps, and begin to follow a three-dimensional path towards an established missed-approach fix point. In visual conditions, the controller may vector the missed-approach aircraft away from other traffic, or instead, vector the other traffic, and/or call for pilot responsibility in maintaining separation. In non-visual conditions with radar coverage, more caution by the controller is necessary in requesting early vectors for aircraft close to the ground, since it is a busy time for the crews in transitioning the aircraft configuration and establishing new flight paths. The ability to fly complex 3-D paths on missed approach using advanced AFCS allows more-complex traffic procedures when such equipment exists in the mix of aircraft.

Note that the pilot may elect at his discretion to execute a missed approach from any point early in the approach. The controller must be prepared to accommodate the pilot. This initiation of missed approach could also occur very late from a point just before touchdown, so that we cannot be assured of "holding short" or not crossing a second operational runway until after touchdown. Knowledge of actual touchdown is obtained visually by the tower controller and is not normally known under poor visibility conditions. Procedures which require "hold short" landings from pilots normally are available only with dry runway surfaces and good visibility.

1.1.3 Initial Approach

At many busy airports there may be a specified set of STAR's (Standard Terminal Arrival Route) which lead aircraft from a holding fix to the outer marker. These are complex 3-D routings which make use of existing navigational aids. Aircraft with advanced AFCS capabilities may fly these STAR's automatically and this capability may allow a mix of more complex 3-D and 4-D STAR's to be specified in the future.

It is possible to consider metering the initiation of STAR's by controlling the departure from holding patterns, and/or modifying the STAR to modify the arrival times at the outer marker. When the final approach to the runway is initiated around the ILS outer marker, the actual arrival time at the runway is pre-determined (since it is not advisable to consider requesting further modifications of the final approach speeds from the ground, although pilots on their own initiative will do this today in good weather to maintain spacing between landings - they are responsible as to how much speed change is safe) given flap settings and aircraft weight.

1.2 Runway Occupancy - Current Separation Rules and Aircraft Performance

In this section we are interested in discussing the current separation criteria for runway operations in VMC (visual meteorological conditions) as specified in the controller's handbook (Air Traffic Control, FAA Document 7110.65D, 1984), and various factors which determine the runway occupancy performance of aircraft. While runway occupancy is not currently a critical factor in determining runway capacity, it could be a critical factor with future improved terminal-area control systems.

1.2.1 Current Runway Separation Criteria

The controller's handbook currently categorizes aircraft for runway separation criteria as follows: (We renamed them, A,B,C to avoid confusion with ILS categories)

Category A - Single-Engine Propeller Aircraft < 12,500 lbs.
Category B - Twin-Engine Propeller Aircraft < 12,500 lbs.
Category C - High-Performance/Heavy/Turbojet, and all others

This categorization is kept simple to avoid undue burden on the mental workload of tower controllers. By simply knowing which single- and twin-engine aircraft are under 12,500 lbs. they currently apply reduced separation criteria from those applied to all other aircraft in VMC conditions. This results in very simple and conservative relaxations of separation criteria. These rules can be made more complex in the future if the controller is given improved, intelligent display systems. The improved separation criteria could then be based on a more-rational application of collision risk analysis. A more complex categorization scheme would be based on better knowledge of aircraft performance capabilities.

1.2.2 Current Separation Criteria - Same Runway, Takeoffs, VMC

Section 3-106 of the controller's handbook requires the following distance (measured in feet) between successive takeoffs:

		Second Takeoff Aircraft		
		Cat. A	Cat. B	Cat. C
First Takeoff Aircraft	Cat. A	3000	4500	6000
	Cat. B	3000	4500	6000
	Cat. C	6000	6000	6000
	Cat. C Heavy	2 mins.	2 mins.	2 mins.

Of course, if the first aircraft "clears" the runway by passing over the end or turning off to the side, then the second aircraft can be cleared for takeoff. Obviously, it is the tower controller's judgement to determine distance, or just when the aircraft clears the runway. Note that this rule apparently sanctions the release of a jet-transport takeoff when a previous single-engine aircraft is 6000 feet (or 1 n. mile) from the takeoff threshold and a few hundred feet in the air. Since they would pass each other roughly 90 seconds later, it obviously presumes the controller will vector the first or second aircraft off the centerline before this occurs.

Section 3-108 sets criteria for "intersection" takeoffs by Cat. A or Cat. B aircraft, i.e. takeoffs from an entry to the runway other than the threshold. For wake-vortex reasons, these aircraft cannot take off behind any Cat. C aircraft for 3 minutes if they use such an entry. However, if the pilots waive this protection they can be released. (This last proviso seems to indicate that liability and not safety is the issue! - the controllers cannot suggest this waiver to the pilot.)

Section 3-106 also covers the case where the preceding aircraft performed a landing. In this case, the landing aircraft must be completely clear of the runway before the second takeoff aircraft can be released. This applies to all categories of aircraft.

1.2.3 Current Separation Criteria - Same Runway, Landings, VMC

Section 3-122 specifies the following distances (measured in feet) between successive landings on the same runway:

		Second Landing Aircraft		
		Cat. A	Cat. B	Cat. C
First Landing Aircraft	Cat. A	3000	4500	CLEAR
	Cat. B	3000	4500	CLEAR
	Cat. C	CLEAR	CLEAR	CLEAR

Note that we can have two or more Category A or Category B aircraft simultaneously on a long runway if they are landings. If the first aircraft is a takeoff, the separation criteria below apply:

		Second Landing Aircraft		
		Cat. A	Cat. B	Cat. C
First Takeoff Aircraft	Cat. A	3000	4500	6000
	Cat. B	3000	4500	6000
	Cat. C	6000	6000	6000

Note here that we can have two Category C aircraft simultaneously on the runway, if the takeoff is at least 6000 feet from the threshold, and VMC exists. Currently, there is no wake-vortex separation for these VMC operations, except when the landing threshold is displaced (See Section 3-106g).

1.2.4 Current Separation Criteria - Intersecting Runways, VMC

Sections 3-108, 3-123, describe separation criteria for operations on two intersecting runways. Essentially, they state that once an operation on the other runway is clear (or anticipated to be clear!) of the second runway, the operation on the second runway can proceed. A landing must cross the second runway or "hold short" to avoid crossing it. A takeoff must cross the second runway or turn to avoid crossing it. In all cases, the controller is allowed to anticipate the clearing action of the first aircraft. Note this is allowed only in VMC. A landing which would fly through the airborne path of a departing heavy aircraft on the crossing runway must be separated by 2 minutes (Section 3-123c).

1.2.5 Expected Landing Occupancy Time - ELOT

"Landing Occupancy Time" is defined as the time from passing the landing threshold to exit from the runway. It depends on the following variables:

1. Approach speed - (aircraft type, and weight)
2. Wind component along runway (groundspeed)
3. Location of runway exits (distance from threshold)
4. Angle of runway exits (speed at exit)
5. Gate location (airline, general aviation)
6. Runway surface conditions (dry, wet, icy)
7. Visibility (day/night, exit marking and guidance)
8. Time to flare and commence braking

Because of all these variables, we cannot predict with certainty the landing-occupancy time for particular aircraft/airline/pilot, nor is it reasonable currently to ask the pilot in advance to exit the runway at a particular location. After touchdown and braking, the controller may request an expedited exit, or ask if the pilot can make the next exit since the pilot can control the degree of braking within fairly-wide limits and can avoid taxiing at slow speed to the next exit. Typical landing-occupancy times for jet transports have been measured between 20 and 100 seconds, in the absence of any pressures to vacate the runway.

An average occupancy time for jet transports is approximately 1 minute, which would convert to a landing-capacity rate of 60 landings per hour (if there were not the more-critical constraints of final-approach spacing which will be discussed later). The lower occupancy times occur when there is an angled intersecting runway at a location where arriving aircraft can gently turn off the landing runway onto the second runway at high speed, and carry out the braking on the second runway.

Many runways currently have "high-speed" exits which are angled off the runway direction. These exits allow the aircraft to turn off at a speed of 20-30 Kts. In no case does the pilot intend to do heavy braking while in these exits. In the past a "drift-off" runway has been suggested. Here the pilot can brake, and turn gently to "drift-off" the landing runway into a side lane where further braking can occur. Such methods would become valuable whenever runway rates approach the capacity rates set by occupancy time.

It is difficult to predict what the actual landing-occupancy time will be for a particular landing, although it is possible to compute a lower bound. By measuring groundspeed on approach from radar tracking and knowing exit location and braking conditions for the runway, the first possible exit may be computed (or we may be able to compute the probability of making an exit and of the corresponding occupancy time).

1.2.6 A Model for Computing Landing Occupancy Time

Symbols

V_{ga} = measured groundspeed on final approach - Kts
V_{ge} = expected taxi speed on runway before exit - Kts
a = expected average deceleration rate - Kts/sec.
D_f = flare distance = 1000 feet
D_b = braking distance
D_t = taxi distance
D_{Ei} = exit distance for i^{th} exit
t_f = time for flare
t_b = time for braking
t_i = time for taxi to exit i
Conversion from Kts to fps = 10/6

Model Relationships

$$t_f = \frac{D_f}{V_{ga}\frac{10}{6}} = \frac{1000}{V_{ga}} \frac{6}{10} = \frac{600}{V_{ga}}$$

$$t_b = \frac{V_{ga} - V_{ge}}{a}$$

$$D_b = \frac{V_{ga} + V_{ge}}{2} \cdot t_b \cdot \frac{10}{6} = \frac{V_{ga} + V_{ge}}{1.2} \cdot t_b$$

$$D_t = D_{Ei} - D_b - D_f$$

$$t_i = \frac{D_t}{V_{ge}} \cdot \frac{6}{10} \quad \text{when } D_t \text{ is positive}$$

$$\text{ELOT} = t_f + t_b + t_i$$

Example

V_{ga} = 120 Kts	D_f = 1000
V_{ge} = 20 Kts	D_{E1} = 2500,
a = 5 Kts/Sec	D_{E2} =4500

$$D_f = 1000 \text{ feet}$$

$$t_f = \frac{600}{120} = 5 \text{ seconds}$$

$$t_b = \frac{120-20}{5} = 20 \text{ seconds}$$

$$D_b = \frac{120+20}{2} \cdot 20 \cdot \frac{10}{6} = 2333 \text{ feet}$$ (It is not possible to make exit 1)

$$D_{t2} = 4500 - 2333 - 1000 = 1167 \text{ feet}$$

$$t_2 = \frac{1167}{20} \cdot \frac{6}{10} = \frac{7000}{200} = 35 \text{ seconds}$$

$$\text{ELOT} = 5 + 20 + 35 = 60 \text{ seconds}$$

If there is a lower bound on expected deceleration, ELOT is a lower bound on occupancy time. There may be some expectation of higher values of α, which translates to a probability that the aircraft will make the first exit. It is possible to conceive of a future system where the controller would be advised of the likelihood of the exit and therefore the occupancy time for each individual aircraft.

1.2.7 Expected Takeoff Occupancy Time - ETOT

There are three components of runway-occupancy time by takeoff aircraft: a time to reach runway centerline from the holding position; a time to lift-off; and a time to fly over and clear the runway.

The time to reach centerline depends on pilot discretion and the distance from the holding point, but this component is not critical since it will normally occur during the prior takeoff or landing roll. It is only critical when releasing a takeoff from the holding position in front of a landing aircraft. The controller usually reminds the pilot in this case by clearing the pilot for an "immediate" takeoff, and may cancel the takeoff clearance and order the pilot to vacate the runway if he dawdles.

The time to lift-off depends on lift-off airspeed and windspeed but varies over a very small range around 30 seconds after start of roll. Given another 15 seconds for communications and delay in initiating takeoff, the aircraft of Category A, B, C are then roughly 3000, 4500, and 6000 feet from the runway threshold; i.e. generally, as each aircraft lifts off the runway, the following landing or takeoff may be cleared following the rules given in Sections 2.2 and 2.3. This rule of thumb is used operationally by tower controllers when there are no other separation constraints. The takeoff aircraft is now committed to takeoff and will not remain on the runway, and it seems sensible that the runway should be considered clear after liftoff for unconstrained VMC operations although that is not precisely what the current ATC handbook states.

Note that if a takeoff can be released every 45 seconds, the hourly capacity of a VMC runway devoted solely to takeoffs would be 3600/45 = 80 takeoffs per hour. As will be seen, this would likely saturate the departure sector for IMC departures where there will be wake vortex or airborne separation requirements for aircraft following the same SID.

Since there is such a small variation in liftoff times, it is not necessary to use any sophisticated techniques to estimate ETOT for a single runway. It may be reasonable to consider such a technique when there are intersecting takeoffs in operation, and we are interested in the time to cross another runway during takeoff at a given weight and windspeed for a given type of aircraft. In this case the controller might be advised about releasing an aircraft of a given type on a crossing runway in front of a landing on another runway when we are tracking the landing speed and can estimate the time of arrival of the landing aircraft at the touchdown and that crossing point. Since the current rules allow the controller to anticipate such crossings, we can devise a display to assist his anticipation, and thereby improve his performance.

1.3. Final Approach Operations - Approach Capacity of a Runway

Under current conditions, the determinant of landing capacity of a runway is the maximum flow rate of aircraft through the final approach process. In this section we will review the current US separation criteria for operating the final approach under both VMC and IMC, and discuss various factors which affect controller, pilot, and aircraft performance. Since this approach process determines landing capacity, we will critically examine these factors in depth, searching for methods of improving future flow rates.

1.3.1 Current Separation Criteria on Final Approach - IMC

Current separation criteria which govern the final-approach process under IMC are radar distances which depend upon the particular pair of aircraft. The US separation criteria classifies aircraft into three groups depending upon their certificated MGTOW (Maximum Gross Takeoff Weight):

(H) Heavy - MGTOW > 300,000 lbs.

(L) Large - 12,500 < MGTOW < 300,000 lbs.

(S) Small - MGTOW < 12,500 lbs.

Other countries currently use slightly-different classification schemes with 4 or 5 classes of aircraft, not necessarily based solely on aircraft weight. Given the above classification, the ATC Handbook 7110.65D, Section 5-72 states the following separation distances (in nautical miles) which should apply at all points in the approach process. (In practice today, they are not rigorously applied between the outer marker and touchdown - radar controllers supply separation at the merge, and usually hand the aircraft over to tower controllers around the Outer Marker). If VMC conditions exist at some point on the glide slope, the controllers will be looking to apply visual separation criteria as discussed later (see Sections 5-124 and 7-32).

		Second Landing Aircraft		
		(H)	(L)	(S)
First Landing Aircraft	(H)	4	5	6
	(L)	3	3	4
	(S)	3	3	3

The separation required prior to wake-vortex considerations was 3 n. miles, and the above matrix shows the additional spacing to accommodate wake vortex. It has been kept simple so that the ATC final-approach controller can apply these separations while working his radar display. With improved automation and displays, this need not be the case, and more-efficient wake-vortex separations can be created.

Notice that with fixed radar-distance separations, the landing interval depends on the speed of the second aircraft. Three nautical miles at 120 Kts means 90 seconds, while at 90 Kts it means 120 seconds. In avoiding the wake vortices which dissipate after a given time, the time interval between aircraft is critical, and obviously these distance separations must be chosen to ensure safety for the fastest aircraft which can be foreseen in the traffic mix. It is not clear that the current separation criteria, based on aircraft weight, are cognizant of aircraft speed or the need to ensure a minimum time interval between successive aircraft in the approach process, but it is clear that these separation criteria can be made more efficient.

Let us briefly review the wake-vortex problem. The wake-vortex strength depends directly on the actual weight of the aircraft and inversely with airspeed. If we have a higher approach speed, it greatly reduces the vortex strength.

If we know the actual weight and planned approach airspeed, we can estimate vortex strength. The persistence of the vortex in time after aircraft passage and its motion relative to the aircraft path is also known. Persistence depends upon meteorological conditions. Non-turbulent, calm, stable atmospheric conditions are necessary for it to persist beyond one minute. Current US approach-separation criteria assume calm, stable atmospheric conditions always exist, and ignores the strength and time interval effects of airspeed.

It is possible to create a much-more-complex statement of required separations on approach which provide both improved safety and higher approach capacity. It would require simple modeling of the wake vortex, and display of desired separations to the controller for each individual pair of aircraft. Let us name this a "Vortex Separation Display" (VSD), and defer further discussion. The VSD has a wider application to approach, landing, takeoff, missed approach, and departure operations.

1.3.2 Operations in the Final Approach Process

As described in Section 1.1.2, in current ILS operations aircraft are vectored into a "merge area" beyond the outer marker, acquire the centerline at an initial-approach altitude, and then acquire the glide slope at the outer marker. In poor visibility pilots track the glide slope and runway centerline until the ground appears, when they may transition to visual guidance to the runway. The above radar-approach separations apply while flight is in non-visual, IMC (Instrument Meteorological Conditions). When the flight comes in visual contact with the ground (the controller may request the pilot to report such occurrence), the controller may turn the responsibility for separation assurance over to the pilot. He will ask if the prior aircraft can be seen, and clear the pilot to "maintain visual separation".

The controller can also clear the pilot for a "visual approach" to any runway at the airport after the flight comes in visual contact with the ground. These relaxations from strict IFR separation standards are in widespread usage today since they increase approach capacity and reduce controller workload. As weather deteriorates in ceiling and visibility, the approach capacity at major US airports decreases. Given these operational practices, final spacing controllers will be more venturesome in establishing initial merge spacings in marginal VMC weather, knowing that spacing errors under IMC can be corrected by the pilots at the end of the approach when visual conditions occur.

If radar separations are about to be violated later in the approach after visual conditions have been reached, controllers will request pilots to "maintain visual separation" from the prior aircraft. (See Section 7-31 of the ATC Handbook). If they refuse, they will be pulled out of the landing stream into a missed approach and returned to the merging area. Normally, pilots accept this responsibility quite readily, and in fact will continue to close the separation to as much as 2 n. miles - well beyond the limits specified for safe vortex separation for the IFR traffic controller.

There are three offsetting considerations; first, the vortex persistence is strongly correlated with calm, stable conditions which often occur in poor visibility, so that in these instances the pilots do not have a wake vortex problem when cleared to maintain visual separation; second, the danger of upset depends strongly upon the reaction time for corrective action by pilots, and when visual conditions exist, pilots will perceive the upset earlier and can pull out of the vortex before their aircraft is seriously upset; third, in visual conditions, pilots are less likely to slip below the glide path where they will encounter the vortices.

The radar separation, S_{12}, is a separation distance to be maintained between the first and second aircraft at all points in the merge and final approach process. In trying to achieve minimal actual separations, the controller must judge the likely groundspeeds of aircraft since they will be different (in general) and thus will create an "opening" or "closing" situation between aircraft pairs. Controllers are limited in their ability to request speed changes in the approach process. Pilots are not usually under any obligation to maintain a constant speed. The pilots have selected an airspeed for final approach, but they will not transmit this to the ground (unless requested), and even if they did, a correction for windspeed along the glide path would be required to estimate the groundspeed. In the face of uncertainty about groundspeeds on approach, the final-spacing controllers use their best judgement but will always allow some buffer or margin to accommodate the errors which inevitably will rise when the pilots use an unexpected speed, or speed change. Given a long runway, some controllers will ask for a common approach airspeed in today's operations.

In the future, to plan a more-efficient merge operation, prior knowledge of planned approach airspeeds must be known to the ground control system, and an obligation placed on the pilot to maintain that speed. Aircraft with an advanced AFCS which can ensure constant groundspeed on final approach would allow more-efficient merging operations. These are the 4-D AFCS which exist today in prototype form. Note that landing distances are dependent on groundspeed, not airspeed, and that flap speeds are usually high enough to allow a considerable increase in approach airspeed. It is reasonable to ask for constant groundspeed on approach from future transport aircraft, but there would be a mix of capabilities for a very long time.

1.3.3 Approach Capacity - Arrival Intervals at the Runway - IMC

Landing flow rates and landing capacity are determined beyond the outer marker when the final-spacing controller merges the landing aircraft into a single flow along the runway centerline. Normally, there are no corrective spacing commands once the pilots have been cleared to conduct the approach. If we are to improve landing capacity, it is clear that the "final approach spacing" or "merge" process must be improved.

The spacing process is complicated by the different speeds which aircraft may elect to use on final approach. Let us consider a pair of aircraft; the first aircraft has a constant groundspeed V_1, the second a constant groundspeed V_2. The required separation is denoted S_{12}. As mentioned previously, there are two cases to be considered: a "closing" case where $V_1 < V_2$; and an "opening" case where $V_1 > V_2$.

In the closing case, S_{12} is achieved when aircraft 1 reaches the runway. To do this the controller must provide a variable spacing at merge which depends on V_1, V_2, and d_1, where d_1 is the distance of aircraft 1 from the runway when the merge occurs (see Figure 1.1).

The variable spacing can be written as $S_{12} + \Delta S_{12}$ where ΔS_{12} is the additional spacing required at the merge point above the required separation at threshold, S_{12}. If we denote d_2 as the merge position for the second aircraft, then

$$d_2 = S_{12} + d_1 \cdot \frac{V_2}{V_1}$$

$$d_2 - d_1 = S_{12} + \Delta S_{12} = S_{12} + d_1 \cdot \left(\frac{V_2}{V_1} - d_1 \right)$$

$$= S_{12} + d_1 \cdot \left(\frac{V_2}{V_1} - 1 \right)$$

Then, $\Delta S_{12} = d_1 \cdot \left(\frac{V_2}{V_1} - 1 \right)$ where $V_2 > V_1$

i.e. the extra spacing required at merge depends directly on the distance of the first aircraft to the runway at merge and the speed ratio of the two aircraft.

This is the nominal spacing required if the speeds are known and are held constant. But there will be errors in the spacing process, and errors in the expected speeds. To ensure that S_{12} is not violated at the runway at the frequency greater than 1% (for example), it will be necessary to provide a buffer for both the merge-spacing error and the approach-speed errors. Let us denote these by ΔSE_{12} and ΔV_{12} respectively. If we know the statistics of these error processes, then we can compute these required buffers. The actual required spacing at merge is then written as:

$$DM_{12} = S_{12} + d_1 \cdot \left(\frac{V_1}{V_2} \right) - 1 + \Delta SE_{12} + \Delta V_{12}$$

The average spacing at runway, and corresponding time interval is:

$$DR_{12} = S_{12} + \Delta SE_{12} + \Delta V_{12}$$

$$t_{12} = \frac{DR_{12}}{V_2}$$

We shall apply these formulas to the case where two aircraft have the same approach speed.

In the opening case, S_{12} is applied at the merge point, and the distance between the two aircraft increases thereafter. The controller spacing error is not important to safety in this case since it will disappear as the gap increases. The controller could apply a spacing-error buffer, or can ignore a minor infringement, which occurs a much larger percentage of occasions. We shall concentrate later on this merge process of slower aircraft, since there are ways of minimizing its effect on the resulting large landing interval and reduction in landing capacity. We can increase landing capacity by concentrating on the problem of the "slower aircraft merge". In this opening case, if we ignore the spacing and speed errors and omit the buffers, the average spacing and average time interval at the runway are given by: (See Figure 1.1)

$$DR_{12} = S_{12} + d_1 \cdot \left(1 - \frac{V_2}{V_1}\right)$$

$$t_{12} = \frac{DR_{12}}{V_2}$$

Thus, if we know the approach speeds, their error, the spacing error, and the merge distance, we can determine the landing intervals for any pair of landing aircraft, and thus the average landing interval. The average landing interval is inverted to give us an estimate of the average landing capacity, and is dependent on both the mix of aircraft types and the landing sequence.

$$\overline{LCAP} = \frac{3600}{\bar{t}_{12}}$$ (where the bar indicates an average)

(average landings/hour = seconds/hour ÷ average landing interval-sec)

Example

Suppose we have three kinds of aircraft whose approach speeds are 90, 120, and 150 kts. The 90 knot aircraft are class S (Small), the 120 knot aircraft are class L (Large), and the 150 knot aircraft are H (Heavy). The outer marker is 5 n. miles from the runway. The sum of spacing and speed errors is equivalent to adding 1 n. miles to spacing for the closing case. There are 25% small, 50% large, and 25% Heavy in the mix of aircraft.

CLOSING CASE: If we have a 90 kts aircraft followed by an H.

$S_{12} = 3$

$\Delta S_{12} = d_1 \cdot \left(\frac{V_2}{V_1} - 1\right) = 5 \cdot \left(\frac{150}{90} - 1\right) = 3.3$ n. miles

$\Delta SE_{12} + \Delta Y_{12} = 1$

$DM_{12} = 3 + 3.3 + 1 = 7.3$ n. mile spacing at merge
(if merge performed when aircraft 1 is at OM)

$DR_{12} = 3 + 1 = 4$ n. miles

$t_{12} = \frac{4}{150} \cdot (3600) = 96$ seconds

OPENING CASE: If we have the 90 knot aircraft merging behind the Large aircraft when the L is at the outer marker

$S_{12} = 4$

$DM_{12} = 4$ (allowing random lateral separation violations to occur by applying vertical separation - see later).

$$DR_{12} = 4 + d_1 \cdot \left(1 - \frac{V_2}{V_1}\right)$$

$$= 4 + 5 \cdot \left(\frac{1-90}{120}\right) = 4 + 1.25 = 5.25 \text{ n. miles}$$

$t_{12} = \frac{5.25}{90} \cdot 3600 = 210$ seconds

If the first aircraft is a Heavy aircraft

$S_{12} = 6$

$DM_{12} = 6$

$DR_{12} = 6 + 5 \cdot 1 - \frac{90}{150} = 6 + 2 = 8$ n. miles

$t_{12} = \frac{8}{90} \cdot 3600 = 320$ seconds $= 5$ mins, 20 sec.

If we assume that there is a random sequence of landings, then the average probability of the occurrence of landing pairs is given below (e.g. the probability of the small-large pair = 0.5 x .25 = .125, etc.)

		Second Aircraft			
		H	L	S	
	H	.0625	.125	.0625	Prob. of occurrence
First	L	.125	.250	.125	of landing pair
Aircraft	S	.0625	.125	.0625	

The landing interval matrix is given by:

		H	L	S	
	H	120	180	320	Arrival Intervals
t_{ij} =	L	96	120	210	at Runway (sec)
	S	96	120	160	

The average landing interval, $\bar{t}_{12}$ = 149.25 seconds,

The average landing capacity, $\overline{LCAP} = \frac{3600}{149.25} = 24.12$ landings/hour

1.3.4 Effect of Sequencing Landing Aircraft

Here we assumed that the occurrence of a landing pair is a random event. If we deliberately control the sequence of landings, we can avoid the larger landing intervals. In this example, we would land all the slower aircraft at 160-second intervals, then transition to the larger aircraft with one 120-second interval, and land them with 120-second intervals; the transition to Heavy aircraft with a 96-second interval, followed by 120-second intervals between all the Heavy aircraft. For this sequence, (assuming 100 aircraft landed and 99 intervals):

$$\bar{t}_{12} = \frac{24 \cdot (160) + 1 \cdot (96) + 74 \cdot (120)}{99} = 129.45 \text{ secs.}$$

$$\overline{LCAP} = \frac{3600}{129.45} = 27.81 \text{ landings/hour}$$

Thus, if all these aircraft were available for sequencing, it would be possible to increase the landing rate from 24.12 to 27.81 landings per hour, a 15.6% increase in capacity. Sequencing landings can increase landing capacity substantially. We will study this effect later.

1.3.5 Effect of Standardizing Groundspeeds on Final Approach

There are penalties associated with having the smaller aircraft in the approach stream of aircraft. Since the faster aircraft need a longer runway, it may be possible to ask the smaller aircraft to maintain a faster speed on approach.

In our example, suppose we asked the small aircraft to fly at 120 knots, the speed of the Large aircraft. This would change the landing interval matrix to the values

t_{ij} =	H	L	S
H	120	180	210
L	96	120	120
S	96	120	120

$\overline{t}_{12}$ = 128.62 seconds

$\overline{LCAP}$ = 27.99 landings/hour.

This is a 16.0% improvement over the base rate of 24.12 landings/hr. If all the aircraft were Large or Small, and flew at a standard approach groundspeed of 120 knots, then the intervals between all landings would average 4 n. miles or 2 minutes. The landing capacity would then be 30 landings/hour.

1.3.6 Effect of Relaxing Separation Requirements at the Runway

It was observed in Sections 1.3.1 and 1.3.2 that the approach separation along the final-approach path is not rigorously applied by practicing controllers, since they may apply visual separations after aircraft reach VMC conditions, and that when given responsibility for approach separation, pilots will close to roughly 2 n. miles at the runway. In our example, suppose we relax the approach spacing at the runway end to exactly 2 n. miles for those cases where there are no wake vortex considerations, i.e. the separation criteria at the runway is 2 n. miles without a buffer for S-L, S-H, L-H cases, and is still 4 n. miles for a Heavy following another Heavy.

t_{ij} =

	H	L	S
H	96	180	320
L	48	90	210
S	48	60	120

$\overline{t}_{12}$ = 121.25 seconds

$\overline{LCAP}$ = 29.7 landings/hour (a 23% improvement)

If we had an improved ATC display, it would be possible in the closing cases to plan the second aircraft's arrival just as the prior aircraft was leaving the runway, i.e. at a time interval ELOT (estimated for the prior aircraft). Suppose we relax the runway-spacing requirement to provide exactly ELOT = 45 seconds with no buffer for the closing cases:

t_{ij} =

	H	L	S
H	96	180	320
L	45	90	210
S	45	45	120

$\overline{t}_{12}$ = 118.8 seconds

$\overline{LCAP}$ = 30.3 landings/hour (25.6% improvement)

1.3.7 Summary - Improving the Approach Capacity of a Single Runway

We can now summarize by noting the variables which determine approach capacity for a single runway:

1) Approach Separation Criteria

currently these are radar distances which depend on the wake vortex classification of landing aircraft pair

2) Mixture of Final Approach Speeds

the mix of aircraft types provides varying speeds dependent on aircraft weight, airport elevation, and temperature, and windspeed

3) Approach Sequencing Strategy

the sequence of landing aircraft arrivals affects occurrence of the larger approach intervals. Sequencing is possible, especially whenever landing aircraft are being held at entry fixes to the terminal area

4) Merge Spacing Error

the inability of the radar controller to accurately space aircraft at entry to the final approach requires a buffer, at least for the closing case when there is no reversion to visual separation by pilots later in the approach. This buffer increases during marginal weather and visibility

5) Buffer for Uncertainty in Approach Speeds

since the radar controller does not know the approach airspeeds planned by each aircraft, and cannot count on the pilots maintenance of a fixed approach speed, there is an additional buffer at merge for the closing case only

6) Merge Distance

the location of the first aircraft whenever a slower aircraft is merged behind it affects the size of the landing interval. It is desirable to merge slower aircraft as close to the runway as possible. It does not affect the landing interval for the closing case

Given these variables, we can list all possible ways to increase the landing capacity of a single runway:

1) Create a more-efficient set of safe approach-separation criteria which uses automation to assist the spacing controller and displays the separation appropriate to each landing pair, given the approach environment. We will develop this topic further below.

2) Adopt a sequencing strategy to avoid larger landing intervals - again a topic for current research and the application of automated decision support for the radar controller.

3) Collect and control the final approach speeds - there are a variety of issues here.

4) Reduce merge spacing errors by displaying to the controller a desired spacing and providing assistance through the display in achieving it.

5) Meter the arrival of slower aircraft to merge closer to runway, and create special merge procedures which provide vertical separation during the merge instead of longitudinal separation.

We should note at this point that it is possible to insert takeoff operations between successive landings so that the larger landing intervals from the extended wake-vortex separations and slower aircraft are not wasted at busy times at major airports. Landing capacity is unaffected until some percentage of takeoffs must be inserted, when landings must be spaced further to accommodate more takeoffs. We will investigate these relationships later in Section 1.5 on mixed operations of a runway.

The most-efficient operation of a single runway occurs when both landings and takeoffs are sequenced and scheduled. In this section, we have concentrated only on the approach capacity of a single runway. We will discuss the approach capacities of multiple-runway systems in a later section. Approach capacity is very crucial since it currently determines the arrival capacity for aircraft at major airports where delay can be severe, causing airspace congestion and holding.

1.4 Initial Departure Separation - IFR Takeoff Capacity of a Runway

When the ground-based ATC system is responsible for maintaining safe separation between successive departures, the release of a takeoff is usually governed by the initial conditions which occur as the second departure becomes airborne. Although successive departures can be dispersed onto diverging paths, there is a small period of time required for pilots to complete the post-takeoff checklist, clean up gear and flaps, transition to instrument flight, etc. Current Terminal Instrument Procedures (TERPS) specify a straight climb to 400 feet before any turn can be made, and it is usually not desirable to require any maneuvers from pilots before that point. Thus, the IFR procedures establish an initial-departure separation which effectively establishes the takeoff capacity of an IFR runway (or pair of close parallel runways with spacing less than 2500 feet which are treated as a single runway).

1.4.1 Current IFR Departure Separation Criteria

The current handbook departure separation criteria are spread through Sections 5-72, 5-113, and 3-106, 3-108 of the ATC Handbook. For non-diverging departure courses where the radar is within 40 n. miles, Section 5-72 requires 3 n. miles radar separation between airborne aircraft. For initial departure courses which diverge by more than 15°, the separation is reduced to 1 n. mile by Section 5-113. Wake-vortex considerations of Sections 3-106, 3-108 stipulate 2 minutes between the release of a takeoff after a heavy departure, but allow a relaxation to the approach separation of 4 or 5 n. miles of Section 5-72.

Given these rules, we can describe the current US initial-departure separation criteria by a matrix of separations when successive initial-departure courses diverge by more than 15° and radar identification can be established within 1 n. mile of the runway:

		Second Departure Aircraft		
		H	L	S
First Departure Aircraft	H	2 mins. (or 4 n. mi)	2 mins. (or 5 n. mi)	2 mins. (or 5 n. mi)
	L	1 n. mi.	1 n. mi.	1 n. mi.
	S	1 n. mi.	1 n. mi.	1 n. mi.

This assumes departures from the same start-of-roll point. If an intersection takeoff follows a Heavy departure, Section 3-107 requires 3 mins. between release. If there are opposite-direction takeoffs, Section 3-93 also requires 3 mins. after a Heavy departure.

If there is no divergence of departure courses, the controller must apply the normal non-wake-vortex separations of 3 (or 5) n. miles at all points along the departure path until he can establish lateral or vertical separation. If the second aircraft is expected to have a faster climb-speed profile, it would close on the first departure, and the controller might be required to apply additional distances (as he does with such landing-approach cases). Normally, he will issue a vector to a divergent course rather than extend its departure release.

It is difficult to ensure initial vertical separation between successive departures. At a later stage when aircraft are a few thousand feet above the airport, the departure controller may be able to establish vertical separation. Maintaining vertical separation during climbout creates a "laddering" process whereby successive aircraft are stepped up the "rungs of a ladder". This is a high-workload process at present, and departure controllers would prefer to be given an excess of longitudinal separation, or to use lateral separation between departures following the same general departure path.

As written, Sections 5-72 and 5-113 of the handbook require 1, 3, or 5 n. miles separation distance at the point when the second aircraft becomes airborne. The time separations required by wake-vortex separation (Sections 3-106, 3108) are intervals between start of roll. Since the aircraft are accelerating, the controllers (given knowledge of the acceleration profiles by type of aircraft and knowledge of windspeed) could release the second departure when distances are less than the nominal value. They would then achieve the nominal value at liftoff. In practice, controllers generally interpret these required distances as distance from the start of roll.

1.4.2 Capacity of a Departure Runway - IFR Departure Intervals

It is clear from the departure-separation matrix that the IFR departure capacity of a runway depends on the mix and sequence of Heavy, Large, and Small aircraft which will be operating from it. Since distance separations are specified (to be easy for the radar controller), the departure intervals are dependent upon the initial climb groundspeeds, and the acceleration profiles to reach those climbspeeds. Thus, the mix of aircraft types, their weight at takeoff, the airfield elevation and temperature, windspeed, etc. are variables in determining IFR-departure runway capacities.

Behind a heavy departure, the current wake-vortex separation is 2 minutes, which is equivalent to a departure rate of 30 departures/hour. But with radar, the current rules relax this time interval to 4 n. miles for another heavy departure, and 5 n. miles for a large or small departure aircraft. Although the wake-vortex separation would seem to require a given safe time interval to allow the wake vortex near the runway to dissipate, these distance separations can allow a smaller interval to exist. For example, the 4 n. miles required when the second departure is a Heavy aircraft can translate to only 95 seconds (instead of 120 seconds) if the takeoff acceleration averages 5 kts/sec and the initial climbspeed is greater than 190 knots (see example following.) This corresponds to a departure capacity of 38 per hour instead of 30 per hour.

It is inconsistent to allow these distance separations and time separations to coexist. In practice, it appears that the tower controllers currently apply the 2-minute separation interval behind a Heavy departure, and that, for simplicity, the criterion is expressed as an integer minute, not as seconds. If so, it is easy to provide the tower controller with a simple departure-interval timer, or countdown display, so that he can work in seconds between particular pairs of departure aircraft.

The distance separations translate to varying departure intervals depending upon the speed and acceleration profiles of departing aircraft. If we know these profiles of the various types of aircraft in the departure mix, we can compute the departure intervals, and consequently, the average departure capacity of the runway.

Example Calculation - Average IFR Departure Capacity, Single Runway

Assume an average acceleration of 5 kts/sec to an initial climb groundspeed of 190 kts. If successive departures on diverging courses require 1 n. mile separation from the start of roll point, and there is no wind;

Then 1 n. mile $= \frac{1}{2} a t_D^2$, or $t_D = \sqrt{\frac{2 \cdot 3600}{5}} = 38$ seconds.

Speed at 38 seconds = $5 \cdot 38 = 190$ kts.

These two aircraft are 38 seconds apart. If their climbspeed is exactly 190 kts, the distance between them during climbout is

$$190 \cdot \frac{38}{3600} = 2.0 \text{ n. miles}$$

If the first aircraft is required to be at 3 n. miles on a non-divergent path, the time difference between the two aircraft is 38 + 38/2 = 57 seconds.

Now, if we assume 20% of the departure aircraft are Heavy, then there will be 2 minute spacing after 20% of departures. All other aircraft will be separated by the 1 n. mile criteria for divergent paths or the 3 n. mile criteria for non-divergent paths. Assume that there are only 25% of all aircraft on non-divergent paths. Allowing 7 seconds for lag in initiating takeoff roll due to communications, etc., the average departure interval is computed by:

$$7 + 0.20\ (120) + 0.25\ (57) + 0.55\ (38) = 66.1 \text{ seconds.}$$

$$\text{Average departure capacity, single runway} = \frac{3600}{66.1} = 54.5 \text{ departures/hour}$$

This may be compared with the VMC capacity of 80 operations/hour, for example, on Page 15.

If we knew the acceleration and climbspeed of every Large or Small aircraft, we could compute the departure interval behind it, and thereby compute the average departure interval for all such aircraft. The departure interval behind a Heavy aircraft is assumed here to be always 2 minutes (although the current rules do allow lesser intervals based on 4 and 5 n. mile distances).

1.4.3 Improving Departure Runway Operations

Because of the acceleration of departure aircraft, there is an "inverse accordion" effect. The time interval between successive departures on the same path is maintained, but the distances stretch out. For example, the one-mile separation used in the previous example increases to a 2 n. mile separation at liftoff and during subsequent climbout if the aircraft have identical climbspeeds (above 190 kts). The opposite effect is often noted during descent to final approach as aircraft slow down. If the climbspeed profiles as a function of takeoff gross weight, and temperature/wind were known to the ATC system, it might be possible to create an automated departure-release display system for tower or departure controllers based on separation required in climbout. This requires further research to see the actual conformance between predicted and actual climb performance over a fleet of aircraft maintained by different airlines.

Notice also that the wake-vortex strength diminishes as aircraft accelerate to higher climbspeeds. The problem is severe in the liftoff region over the runway. Aircraft may encounter the vortex later in the departure when they climb through the vortex, but the strength may then be insignificant. If knowledge of liftoff points and climb angles by aircraft type and weight were known, more-efficient departure intervals could be safely computed and displayed to controllers for the wake-vortex case behind a heavy departure.

Tower controllers can deliberately select initial-departure courses to ensure at least 15^{o} divergence between successive departures, and thereby maximize runway departure capacity, but they then handoff departures to the departure sector(s) which could be overloaded by the resulting traffic flow. Thus, the actual limit on departure capacity may be the capacity of the first departure sector, unless care is taken to provide multiple departure sectors and/or efficient departure procedures.

There are various technological improvements to assist in increasing departure-sector capacity. Today, the pilots will normally switch on their autopilot as they reach 400 feet above the airport and are switched from tower to departure controller. Departure control may have assigned a SID, or may be vectoring the aircraft. Future advanced AFCS could select and automatically fly the complete SID, but as seen above, successive departures on the same SID reduces departure capacity. However, it is possible to modify today's SID by creating left, center, and right alternate paths for the SID. Then, when "15^{o} left" is given as the initial departure vector, the AFCS is commanded to fly the left alternate path which would provide some specified lateral separation from the central SID. We shall call this the "Offset SID" procedure.

With the use of digital datalink, other possibilities exist. Some current military systems allow the controller to draw a modified conflict-free SID on his display screen, transmit it to a particular aircraft, and then be supported by automatic conformance monitoring. The "ad-hoc SID" disappears from his screen, but a significant deviation will cause it to reappear with an alert showing the aircraft's deviation. In this way, the departure controller can lower his workload by establishing the complete departure paths for each aircraft at one time rather than deal with a multiple, dynamic set of vectoring commands. The aircraft receives the complete SID and can display it to the pilot who can ask his advanced AFCS to fly it automatically. Vortex monitoring would be added to assist the civil departure controller in generating these alternate departure paths.

A second application of digital datalink involves "altitude chaining". This is a new altitude-control concept which provides automatic "laddering" of climbing or descending aircraft. The pilots receive their altitude clearances by datalink or voice synthesis as other departing aircraft clear altitudes above. The controller creates and controls a "chain" of climbing aircraft whereby each aircraft can be cleared to an altitude 1000 feet below the prior aircraft. As the first aircraft clears an altitude, the chaining control process on the ground automatically creates and transmits a new altitude clearance for the following aircraft and also displays it to the controller for monitoring and transmittal to non-datalink aircraft. As aircraft climb out, pilots receive ever-increasing altitude clearances on their display and can transfer these clearances to their autopilot.

The process would have a conformance monitor to warn both pilot and controller of significant deviations and the AFCS of participating aircraft could be required to have an assigned altitude capture mode. The controller can rearrange his departure chains as lateral or longitudinal separations are established. We will discuss this process further during our research, since it also applies to descending aircraft. It is mentioned here to indicate that there are methods of overcoming any workload or airspace capacity restrictions on departure flow from a runway or major airport.

1.5 Mixed Takeoffs and Landings - Operational Capacity of a Single Runway

The single runway has separate capacity rates for landings, takeoffs, and total operations at any given mix of aircraft. There are significant capacity advantages in simultaneously using a single runway for both takeoff and landing operations, since the tower controller can insert a large flow of takeoffs into the gaps in the full-capacity landing flow with no degradation of landing capacity. The possibility of a missed approach in IMC conditions (where both the landing and takeoff aircraft might then be simultaneously departing from the runway area) requires that there be sufficient longitudinal spacing between approaching and departing aircraft. As the percentage of takeoffs is increased, we reach the point where no more insertions can be freely made in the full-capacity landing flow, and then landings must be further spaced and scheduled to accommodate the very-high flow rate of takeoffs.

1.5.1 Current Separation Criteria - Insertion of Takeoffs Ahead of Landings

Under visual conditions, the table in Section 2.3 shows that a landing aircraft of given class may be cleared if the departing takeoff is 3000, 4500, or 6000 feet down the runway. In this case, the pilots (and tower controllers) are in visual contact and the responsibility to maintain separation is placed upon the pilots. In non-visual conditions, Section 5-114 of the current ATC Handbook 7110.65D (1984) states that under radar separation the radar controller must "separate a departing aircraft from an arriving aircraft on the final approach by a minimum of 2 n. miles if separation will increase to 3 miles (5 miles when 40 miles or more from the antenna) within 1 minute after takeoff."

This is interpreted by radar controllers to mean that the arriving aircraft must be at least 2 n. miles from touchdown when the departure is released, although subsequently the two aircraft will be less than the separation at release (since the takeoff aircraft must accelerate up to the approach speed before the separation between the two aircraft stops decreasing). For example, if the approaching aircraft is at 2 n. miles and has a 120 kt. groundspeed, and the departing aircraft has an average acceleration of 5 kts/sec. then the aircraft will continue to close for 120/5 = 24 seconds after release, and the minimum separation at that time is given by

$$SEPMIN = SEPREL - \frac{V_{app}^2}{2a}$$

where SEPREL = separation required at release = 2 n. miles

V_{app} = approach groundspeed

a = takeoff acceleration

In our example, SEPMIN would be 1.6 n. miles

If the controllers worked the problem using the approach speed to ensure that SEPMIN was 2 n. miles, then SEPREL would have to be 2.4 n. miles. But to compute the varying SEPREL, they would have to know the approach groundspeed, the average acceleration of the departing aircraft (given wind, temperature and weight), and whether the departure speed exceeded the approach speed.

The critical case which establishes IMC arrival-departure separation occurs whenever the landing aircraft decides to carry out a missed approach after a departure. Remember from Section 1.4, that for consecutive departures where the departure paths diverge by 15°, the radar controllers are required to provide only 1 n. mile separation. By vectoring one or the other aircraft, the radar controller can establish an identical situation for the missed approach/departure case. If the prior departure was a Heavy aircraft, vectoring is advisable anyway to ensure separation of the missed-approach aircraft from the wake vortex. There is no guidance in the ATC Handbook about applying the departure-separation criteria under diverging courses (or the wake-separation criteria) to the missed approach/departure situation.

The puzzling part of Section 5-114 comes from the condition that 3 n. miles separation be established within 1 minute after takeoff. This would likely require a vector to diverging courses since otherwise it implies an extremely-high initial-climbout speed for the departing aircraft. If the controller released a departure with the arrival at 2 n. miles and 120 kts, the departure would have to accelerate to 360 knots groundspeed to meet the condition (at 6 knots/sec). If he released it at 2.4 n. miles, the speed would be 312 knots and an average acceleration of 5.2 kts/sec. Unless the departure is a high-performance aircraft, the controllers would have to use lateral separation to avoid the 3 n. miles within 1 minute.

Notice the section does not explicitly state that a missed approach is occurring. In our example, at 1 minute, the approach aircraft has arrived at the threshold of the runway, and even faster aircraft would normally be on the runway, so it is difficult to understand the "3 n. miles in one minute" requirement. We shall ignore the conditions actually specified by Section 5-114, and like controllers in the field, shall interpret it as requiring 2 n. miles at release for all aircraft pairs.

The possibility exists that a departure could be constrained by the 2-minute wake-vortex requirement of a prior departure even though there has been an intervening landing operation which is now clear of the runway. (As explained in Section 1.4, it is not always 2 minutes since 4 or 5 n. miles can be substituted which may decrease the time separation substantially.) The interval between the two takeoffs would be occupied by the time required for the landing aircraft to fly 2 n. miles or more to the runway, land, and then clear. It could be less than 2 minutes, but we shall ignore such a rare occurrence in our estimation of mixed-operations capacities.

In summary, the separation criteria for mixed operations are not clearly written. The simple requirement of 2 n. miles before release is used in this report. It would be preferable to use time-separation criteria if they could be provided to the controller by future ATC systems.

1.5.2 Insertion of Takeoffs into a Capacity Landing Flow

The current operational procedures allow the final-spacing approach controller to work independently to establish the approach spacings. Even at maximum landing rate, there are still substantial gaps in the landing flow available to handle a sizeable takeoff flow with no impact on the landing capacity such that, generally, one or more takeoffs can generally be inserted by the tower controllers after every landing. They must make a judgement about the feasibility of an insertion as the first landing passes the threshold, and then clear the departing aircraft to the runway centerline "to hold" waiting for the landing aircraft to clear the runway. If it's clear before the next landing aircraft is at the 2 n. mile point, the takeoff clearance can be issued. Possibly, a second takeoff aircraft can then be cleared to the centerline to hold, awaiting sufficient separation from the first departure, if the tower controllers judge that this event will also occur before the next landing reaches the 2 n. mile point. The tower controllers use visual or radar information to make this judgement.

It would be easy to aid the controllers' decision making by using a computer display which uses predicted event times for each aircraft type rather than leaving them to make judgements based on a distance-based radar display. The ETTD (Estimated Time To Touch Down), or a simple red-yellow-green signal could be used to indicate the feasibility of inserting the next takeoff based on distance and approach speed and the departure intervals required between types of departing aircraft. The tower controllers would have to enter the landing exit, and start of roll times.

The operational situation is best explained by using the small idealistic example of Section 1.3, typical of the mixed operations found on a single runway at a major US airport during IMC. We shall assume a mix of Heavy, Large, and Small aircraft in the proportions of 25, 50, 25 percent respectively in both the landing and takeoff flows.

If we assume a random occurrence of pairs within the landing and takeoff sequences, we get the following p_{ij} matrix

		H	L	S	
	H	.0625	.125	.0625	probability of
p_{ij} =	L	.125	.250	.125 =	occurrence of
	S	.0625	.125	.0625	the pair ij

With an outer marker at 5 n. miles, and a spacing buffer of 1 n. mile for the closing cases, this gives us the following t_{ij} matrix of landing intervals (See Section 1.3):

$$t_{ij} = \begin{array}{c|ccc} & H & L & S \\ H & 120 & 180 & 320 \\ L & 96 & 120 & 210 \\ S & 96 & 120 & 160 \end{array} = \begin{array}{l} \text{minimum approach} \\ \text{intervals for the} \\ \text{pair ij (seconds)} \\ \text{under IMC} \end{array}$$

The approach ground speeds are assumed to be 150, 120, and 90 knots for the Heavy, Large, and Small aircraft. For simplicity, we shall assume that each type has an expected landing-occupancy time, ELOT = 45 seconds, and an average takeoff interval time, ETOT, of 64 seconds (See Section 1.4.2).

The above example has an average landing interval of 149.2 seconds and a corresponding landing capacity of 24.1 landings per hour.

If we subtract ELOT, from t_{ij}, we get the intervals when the runway is idle between landings, I^o_{ij}:

$$I^o_{ij} = \begin{array}{c|ccc} & H & L & S \\ H & 75 & 135 & 275 \\ L & 51 & 75 & 165 \\ S & 51 & 75 & 115 \end{array} = \begin{array}{l} \text{idle runway intervals} \\ \text{between landings} \\ \text{at capacity flow rate (seconds)} \end{array}$$

I_{ij} = average idle time between landings = 104 seconds

If we now subtract the time required for the second landing aircraft to fly from the 2 n. mile point to the runway, (e.g. 80, 60, 48 seconds for S, L, H) we get the time intervals available for inserting one takeoff, A^1_{ij}:

$$A^1_{ij} = \begin{array}{c|ccc} & H & L & S \\ H & 27 & 75 & 195 \\ L & 3 & 15 & 85 \\ S & 3 & 15 & 35 \end{array} = \begin{array}{l} \text{time available} \\ \text{to insert one takeoff} \\ \text{(seconds)} \end{array}$$

Since every entry in the matrix is positive, we can insert one takeoff into every landing interval. The only critical landing pairs are the Large and Small aircraft followed by a Heavy where there is only three seconds on average to release the intervening takeoff. We create an insertion matrix which counts the number of takeoffs inserted in each interval. At this point we only insert one aircraft.

n_{ij} =		H	L	S		
	H	1	1	1		number of takeoffs
	L	1	1	1	=	inserted in each
	S	1	1	1		landing interval

$\bar{n}_{ij} = 1$

The corresponding runway operations rate is 2(24.1) = 48.2 operations/hour with 50% landings and 50% takeoffs.

We have assumed that the average takeoff interval is 64 seconds, so that we can adjust the availability matrix by subtracting 64 from each entry in A^1_{ij} to show the time available to insert a second takeoff, A^2_{ij}:

A^2_{ij} =		H	L	S
	H	-37	11	131
	L	-61	-49	21
	S	-61	-49	-29

We can still insert a third takeoff in the H-L and L-S pairs, and actually three more in the H-S pair before the available intervals turn negative. This would give an insertion matrix, n_{ijmax}:

n_{ijmax} =		H	L	S
	H	1	2	4
	L	1	1	2
	S	1	1	1

The average insertion $\bar{n}_{ijmax}$ = 1.44 takeoffs per landing.

The corresponding runway operations rate is (1 + 1.44) • (24.1) = 58.8 operations per hour. This consists of 24.1 landings per hour (the capacity landing rate) and 34.7 takeoffs per hour which can be freely inserted without reduction of landing capacity. Now the mix of operations is 59% takeoffs and 41% landings.

Corresponding to this n_{ijmax} matrix is another idle-time matrix, I^n_{ij}, which shows the runway idle time between landings when n takeoffs are being inserted.

I^n_{ij} =

	H	L	S
H	27	11	3
L	3	15	21
S	3	15	35

The average idle time I_{ijmax} = 14.25 seconds, for all the takeoffs inserted in any landing gap. In some cases there is very little buffer between operations (especially H-S, where 4 takeoffs are inserted with only 3 seconds buffer for all of them). In practice the landing spacing will not be perfect, and more or less time will exist for the particular case. It will not be possible to insert n takeoffs every time.

The method of this example produces the maximum insertion rate for takeoffs in a capacity landing flow, and shows the factors which determine the maximum insertion rate. If we wish to have yet a higher rate of takeoffs in mixed operations, we must advise the landing spacing controller to decrease the actual landing rate, i.e. landings no longer have absolute priority over takeoffs.

1.5.3 Scheduling Landing and Takeoff Operations on a Single Runway

There are capacity advantages in coordinating the takeoff and landing operations on a single runway. The final spacing controller would be shown a desired spacing such that insertions of exactly n takeoffs are planned between scheduled landings, leaving no idle time for the runway. If we accept the requirement that no two aircraft operate on the runway at the same time, this technique provides the ultimate operational capacity of the runway. Note that current rules do allow simultaneous use of the runway for smaller aircraft in VMC.

We can continue our example to show what this ultimate operations capacity would be if we stretched each insertion interval to add one more takeoff. The n_{ij} matrix becomes

n_{ij} =	H	L	S
H	2	3	5
L	2	2	3
S	2	2	2

$\bar{n}_{ij} = 2.44$
Takeoff mix = 70.9%

Given A^{n}_{ij}, we can compute a "stretch" matrix, giving the increase in landing intervals for each landing pair:

Stretch =	H	L	L
H	37	53	61
L	61	49	43
S	61	49	29

The new stretched landing intervals will be:

t_{ij} =	H	L	S
H	157	243	381
L	157	169	253
S	157	169	189

The average interval, $\bar{t}_{ij}$ = 200.3 seconds, which corresponds to a landing rate of 18.0 landings per hour. Given the insertions of 2.44 takeoffs per landing, the takeoff rate is 43.9 takeoffs per hour, for a total operations rate of 61.9 operations per hour.

If we reduce the landing rate to zero, the maximum takeoff rate (100% takeoffs) is 3600/64 = 56.25 takeoffs per hour. We can show the effect of increasing takeoff rate on landing capacity and operations capacity in Figure 1.2 for the example runway case of this section. Notice that the landing capacity remains constant as an increasing number of takeoffs are freely inserted in the capacity landing flow gaps. Once the gaps are all filled, the landing capacity must be reduced. The operations capacity of the example runway appears to be reached under scheduled operation of the runway with 70.9% takeoffs in the mix where a maximum average operations rate of 61.9 aircraft per hour is reached, consisting of 18.0 landings and 43.9 takeoffs.

1.5.4 Improving Mixed Takeoff/Landing Operations on a Single Runway

The idealistic example of the previous sections applies to operations under IMC. We assumed that an approaching aircraft had to be at 2 n. miles to release a departure, and that all aircraft had fixed values of ELOT and ETOT. The purpose of the example is to illustrate a number of facts: 1) takeoffs can be freely inserted in a maximum landing flow at sizeable takeoff flow rates; 2) there often is substantial idle time for the runway even when takeoffs are being inserted; 3) the maximum operations rate is achieved when runway operations are scheduled to minimize runway idle time.

Under VMC, the maximum landing rate will be higher and the insertion rates for takeoffs correspondingly lower. The VMC separation conditions of 3000, 4500, 6000 feet for various classes of arrival/departure aircraft require the approaching aircraft to be roughly 45 seconds from touchdown at the release time for the takeoff. In these conditions, tower controllers use visual information and exercise their judgement to achieve such separations. A missed approach in VMC is rare, and the pilots would have visual contact and are responsible for maintaining separation. If radar tracking were used to predict ETTD (Estimated Time of Touchdown), the simple display of this value would greatly aid the decision-making of tower controllers, and then the VMC arrival/departure separation criteria could be time-based.

The same information would be useful and more efficient in establishing criteria under IMC where the actual times that a landing or takeoff aircraft clear the runway may not be obtained through visual means. Pilot reports or ASDE (Airport Surface Detection Equipment) are not satisfactory sources, due to their delays in confirming that the runway is clear. Tower controllers could be given an interactive display of runway occupancy, where they enter start-of-roll times and are assisted in deciding on insertion of aircraft of given types. The entry could also provide a signal to the departure control sectors that this aircraft has started its takeoff. The lack of visual cues is a severe handicap to mixed operations of a runway under IMC conditions. If advanced technology could provide surveillance data on runway occupancy, it would allow a greater operational capacity of airport runway systems in these conditions.

The critical separation under IMC is the current requirement for 2 n. miles (increasing to 3 n. miles) to ensure that the radar controller has valid radar separations in the event of a missed approach. If the divergent course separation of 1 n. mile could be applied in this case, it would increase the operational capacity of the runway. This would require increased confidence that both aircraft were conforming to their divergent assigned missed-approach and SID paths. This suggests that aircraft which could fly these paths automatically could have the one-mile-separation criteria. The ATC system would then have to be cognizant of the capabilities/status of each individual aircraft in applying such relaxed criteria, since there would be a mix of capabilities in the landing and takeoff flows. If we assume it takes 38 seconds for the takeoff of the aircraft to reach one mile from start of roll, the free insertion rate of 34.7 takeoffs per hour, for our example, increases to 49.7 takeoffs per hour. This increases the operations rate for the runway from 58.8 to 73.8 operations per hour, or a 25% increase in capacity.

1.6 Simultaneous Operation of Multiple Runways

If two parallel runways are separated by sufficient lateral separation, their simultaneous operations can be regarded as independent, and thus the capacity of the parallel runway system is twice the capacity of a single runway. In this case, simultaneous landing or takeoff operations can take place on the two runways without any coordination, and a separate ATC controller and frequency assigned to each runway. However, at some point the runways are considered to be closely spaced, the simultaneous operations become dependent, and the capacity of the parallel runway system is reduced and eventually must be treated as a single runway. Crossing runways always create dependent operations between takeoffs and landings.

1.6.1 Current Separation Criteria - Simultaneous VMC Operation of Parallel Runways

In visual conditions, independent simultaneous landing and takeoff operations can be made from runways which are only a few hundred feet apart depending on the type of aircraft. The ATC Handbook 7110.65D currently has the criteria shown below: (Section 3-92)

Aircraft Type	Runway Separation (feet)	
	Centerline	Edge
Cat. A - Single-Engine Piston	300	200
Cat. B - Twin-Engine Piston	500	400
Cat. C - Other	700	600

If the aircraft are of different types, the higher class and larger separation governs. The edge separation ensures that wing tips are separated if aircraft move to the edge of the runway during operations. These criteria allow two jet-transport aircraft to takeoff or land simultaneously on runways whose centerlines are only 700 feet apart in visual conditions when pilots are responsible for maintaining separation. Section 3-91 states that an arrival aircraft is to be considered as a departing aircraft upon crossing the threshold or touching down.

Section 7-33 describes the criteria for Visual Approaches to parallel runways. When the ceiling is at least 500 feet above the minimum vectoring altitude (typically 2000 feet above airport elevation), and visibility 3 n. miles or greater, aircraft are informed that parallel approaches are in operation, and one of the pilots or the tower controller can provide visual separation, then simultaneous visual approaches may be conducted. If the runways are separated by more than 700 feet but less than 2500 feet, there is an additional wake-vortex restriction that a Heavy aircraft cannot overtake an aircraft on approach to the other runway, but if they are separated by more than 2500 feet, this restriction is removed.

This restriction is puzzling since apparently a Large or Small aircraft is allowed to overtake a Heavy aircraft, where the exposure to wake-vortex risk is identical to the case where the Heavy overtakes these aircraft. Apparently, there is a presumption in 7-33a that Heavy aircraft have faster approach speeds than Large or Small aircraft (which need not be true). Note that for runways less than 2500 feet apart, wake-vortex upsets can be avoided by having aircraft land in pairs at the same approach speed. The following pair would then be subject to any wake-vortex criteria. This "paired" landing procedure for closely-spaced parallel runways in VMC is currently used at Denver and Los Angeles.

If there is a departure operation by a Heavy jet aircraft, the subsequent takeoff requires a two-minute separation on parallel runways less than 2500 feet apart (Section 3-109f-2). Similarly, any IFR aircraft (not VFR?) landing behind a Heavy jet landing requires a 2-minute separation on parallel runways less than 2500 feet apart (Section 6-5). As explained in Section 1.2.3 of this report, there are no wake-vortex separation criteria for VMC operations except in the case that there is a displaced landing threshold. (Section 3-106g)

1.6.2 Current Separation Criteria - Simultaneous IMC Operation of Parallel Runways

For runways separated by less than 2500 feet, operations under radar control when wake-vortex considerations are present require that the two runways be treated as a single runway (Section 5-72d,e Note).

For runways separated by between 2500 and 4300 feet, Section 5-125 allows dependent parallel ILS approaches. The normal 3 n. miles for longitudinal separation between approaching aircraft can be reduced to 2 n. miles diagonal separation after both aircraft are established on their localizers. At turn-on, 3 n. miles or 1000 feet separation must be provided. Wake-vortex separations still apply to successive-approach aircraft on the same localizer. Approach Control must monitor these separations and retain capability to override local control.

For runways separated by more than 4300 feet, Section 5-126 allows independent simultaneous ILS approaches. Aircraft are required to have at least 1 n. mile of straight flight prior to intercepting the localizer, cannot have an intercept angle greater than 30 degrees, and must have 3 n. miles or 1000 feet separation provided at turn-on to the localizer. All approaches must be monitored by separate ATC controllers to ensure that aircraft do not enter the NTZ (No Transgression Zone). This zone (at least 2000 feet wide) is established equidistant between runway centerlines and must be depicted on the approach monitor display. The monitoring controllers are instructed to warn the pilot of impending penetration of the NTZ, and issue instructions to return to the localizer immediately. When an aircraft has penetrated the NTZ, the monitoring controllers are instructed to vector aircraft on the adjacent localizer to avoid the penetrating aircraft.

Simultaneous, independent departures are allowed on runways separated by more than 2500 feet under radar control if the initial courses diverge by more than 15 degrees (Section 5-113.c). If there is no radar coverage, the runways must be separated by more than 3500 feet, and the initial courses must diverge by more than 45 degrees (Section 6-10.b).

Simultaneous, independent operations by departures and arrivals are allowed on runways separated by more than 2500 feet under radar control if the initial course or missed-approach course diverge by more than 30 degrees (Section 5-115.a). If the runway thresholds are staggered, the lateral separation of 2500 feet can be reduced by 100 feet for every 500 feet of stagger (down to a minimum of 1000 feet lateral separation) for the case where the arrival is on the nearer runway. Conversely, if the aircraft is on the farther runway, the lateral separation must be increased above 2500 feet by 100 feet for every 500 feet of stagger (Section 5-115.b). Thus, a given pair of parallel runways may allow independence of departures and arrivals when the arrivals are on the nearer runway, but require the 2 n. mile separation for release of a departure on the nearer runway (when the arrival is on the further runway).

There is a second situation where dependent operations between arrivals and departures is allowed called the "Dual Lane" operation. The lateral separation between departures and arrivals in IMC is required to handle the situation where a missed approach occurs and the radar controller is faced with two aircraft simultaneously in the departure zone. When visual conditions exist at the runway, and the tower controller can see touchdowns of the landing aircraft, the threat of this situation is removed. Thus, the departure can be released after touchdown of the landing even though the departing aircraft will enter IMC conditions shortly after lift-off. Dual Lane departure/arrival operations of jet transport aircraft can be continued down to the 700 foot lateral separation required for VMC operations even though IMC conditions generally exist. The weather requirement is that tower controllers can see touchdowns. These conditions are summarized in Figure 1.3.

1.6.3 Improving the Independent Operation of Close Parallel Runways

Operations on runways closer than 2500 feet are currently restricted by wake-vortex considerations at touchdown or liftoff. IMC operations on runways spaced further apart than 2500 feet are restricted by considerations in ensuring safe parallel flight in approach or departure zones, and in safely performing the merge operations as aircraft converge on the parallel-approach centerlines beyond the outer marker of the ILS.

Parallel-departure operations in IMC are allowed down to 2500 feet lateral spacing by simply imposing a 15 degree divergent course restriction, and a similar divergence restriction of 30 degrees is imposed between missed-approach and departure aircraft. These aircraft are guaranteed to start from runway centerlines, and diverge thereafter; but for the case of parallel-approach operations, aircraft are required to converge and acquire the runway centerline, and thence to sustain close parallel flight to the runway, and thereafter if missed approaches occur. Thus, parallel-approach operations currently become dependent at 4300 feet lateral separation and are not allowed below 2500 feet separation. But the capacity of the approach processes is also affected by the imposition of 3 n. mile separations (or 1000 feet in altitude) between merging aircraft on either runway. Since the runways are usually separated by less than 3 n. miles, the capacity will be reduced from their independent operation values because of the need to maintain separations as aircraft converge on each other in the merge area.

This suggests that approach capacity of close parallel runways can be improved by adopting "split-approach operations" where the final approach paths are angled to converge onto the runway centerlines. It also suggests that MLS or RNAV guidance and coupled-approach capability should be factors in establishing higher-capacity operations of closely-spaced parallel runways. An example of one possible configuration for split approaches is shown in Figure 1.4. With such convergent-approach operations, it should be possible to achieve independent operations to closely-spaced runways down to 2500 feet lateral separation where wake-vortex considerations currently apply to touchdown operations.

As can be seen, by angling both approach paths by 15^{o}, the separation at turn-on to final approach, at the outer marker, and at visual contact with the airport are all increased, or inversely, the parallel runway lateral separation can be smaller. For example, the separation between outer markers at 6 n. miles from the runways is 3.1 n. miles more than runway separation when 15^{o} convergence is used, so that independent merging operations can be carried out to feed both runways from either side. Once established on the approach paths, the NTZ (no transgression zone) would be larger than that provided for parallel approaches. At the point where visual conditions are reached, both pilots are oriented towards each other and the runways. Provision of a single MLS, or dual angled ILS will provide guidance to aircraft, and automatic coupling of aircraft to its angled, convergent approach localizer can be required for simultaneous operations.

The split approach necessitates a small turn to the runway direction which places capability requirements on the pilot or flight control system. At night, or in poor visibility, there is a chance of confusing the landing runways, particularly if a crosswind is present. The use of different colors in the approach lighting may be required, especially for the "rabbit" which runs along the centerline of the approach lighting system, or a lighted "fence" can be used to denote a non-transgression zone. Using either MLS, ILS, or RNAV as navigation and guidance inputs, the small final turn (15^{O} or less) can be flown automatically by advanced flight-control systems at a height of 400 feet above the runway elevation to join a short final path of roughly 4000 feet to touchdown. At any point on the approach, the missed-approach path requires a turn to a divergent direction as soon as possible in the missed-approach procedure.

There would likely be a requirement for pilots to have demonstrated their capability to conduct such an angled approach procedure given their equipment capabilities, and to maintain currency in such procedures. The procedures and geometries would have to be generally similar for application at various airports. Research, simulation, and flight test would be required to demonstrate such angled approaches and determine the piloting, navigation and guidance, and ATC parameters for safe procedures.

The capacity improvement of split approaches results from having two independent merging operations to feed the parallel runways. Landing capacity is established beyond the outer marker as explained in Section 1.3. The ATC separation criteria, if applied between aircraft on opposite parallel approaches less than 3 n. miles apart, cause a gradual loss in approach capacity due to lengthening one of the approach paths and due to stretching the inter-arrival spacing on dependent parallel runways. The lateral separation critical to approach capacity is not between the runways, but rather the lateral spacing between outer markers, or point of initiation of the final approach.

Another solution to improved operations of parallel approaches, which is practiced today, is to perform a "step-over" maneuver after aircraft have the runways in visual contact. This is often a "safety-valve" in spacing a faster aircraft behind a slower aircraft on approach. The spacing controller may be more venturesome in establishing such spacings if he knows that the slower aircraft can be pulled late in the approach to land visually on a close parallel or other runway. In this case, the pilot must perform an S-turn instead of the single turn of the convergent-approach scheme. Another possibility for aircraft with advanced flight-control systems is to initiate the approach on a widely-spaced path, and to step over to the centerline of the closely-spaced runway after achieving visual contact. This is also illustrated in Figure 1.4, but the need for visual descending double or S-turns at low level makes this solution inferior to the convergent split approaches, where ground-based guidance makes it available to a wider set of aircraft, and there is a single, small turn to the runway centerline.

1.6.4 Current Separation Criteria -- VMC Operation of Crossing Runways

The general principle underlying the ATC rules (Sections 3-108, 3-123) governing visual operations of crossing runways is that a runway can operate if the preceding operation on the other runway has cleared it by crossing, turning off, or holding short, or if the ATC Tower controller anticipates that one of these clearing conditions will occur (Sections 3-104, 3-127). The wake-vortex separation rules (if one aircraft is a Heavy) require that the airborne flight paths do not cross (Section 3-106.c), or 2-minute separations if they do cross. This simple specification that "airborne flight paths not cross" is inadequate since the wake vortex could still drift back across the other runway.

This anticipation concept has led to "Hold Short" landing operations on intersecting runways in good weather. This has been formalized in FAA Order 7210.3-1227, which authorizes simultaneous landing operations on intersecting runways under the following conditions:

1) Runways are dry and braking action is good
2) VFR, or visual approach separations only
3) Hold-short instructions are issued to one pilot in time to achieve his concurrence
4) Distance to intersection is known and issued to pilot upon request. The controller knows the aircraft type and has knowledge that it is capable of "hold short" landings within the intersection distance.

The problems of simultaneous missed approaches and wake-vortex separation are apparently circumvented by relying upon the visual-approach weather requirements to allow assignment to the pilots of responsibility for separation assurance from the other aircraft and its wake vortex. At least, it seems implicit that the controller will not anticipate a missed approach.

This "Hold Short" operation provides additional landing capacity at many major airports in marginal weather conditions. (Visual Approaches can be conducted down to ceilings of minimum vectoring altitude plus 500 feet, and visibilities of 3 n. miles or better.) The loss of multiple approaches as ceiling or visibility drop below these values causes a major reduction in arrival capacity for the airport, since there are no criteria currently for simultaneous approaches to convergent, intersecting runways under IMC conditions. It is a topic of current research by the FAA (see FAA-EM-82-4, Requirements for Instrument Approaches to Converging Runways, L.C. Newman, W.J. Swedish, T.N. Shimi, Mitre Corp., September 1981, and other reports).

1.6.5 Current Separation Criteria - IMC Operation of Crossing Runways

Under radar operations, Section 5-113.b.2 authorizes an IMC departure when the preceding departing aircraft has passed the intersection (or is anticipated to do so) provided that the runways diverge by more than 15 degrees. Presumably, Section 3-106.c applies and the preceding aircraft should not be airborne through the intersection if it is a Heavy aircraft. This is the only IMC operation currently authorized for crossing runways. It is not clear why the preceding aircraft could not be an arrival, and it is possibly an oversight in writing Section 5-115 of the ATC Handbook. Certainly, controllers currently do allow IMC departure release after a crossing landing has touched down and cleared the intersection.

Currently, there are no authorizations for simultaneous, or dependent landing operations on crossing runways in IMC conditions. In this case, the weather minima for landings on crossing runways is that for Visual Approaches - 500 feet above minimum vectoring altitude and 3 nautical miles visibility. This allows visual separation if a missed approach occurs.

1.6.6 Landing Operations on Crossing Runways in IMC

It is difficult to foresee the operation of simultaneous landings on crossing runways under IMC conditions where ATC is responsible for safe separation. Unlike the split approach to close parallel runways, the landing aircraft will actually cross the other landing path. If the crossing points are near touchdown points, ATC could schedule alternate touchdowns, (using advanced technology) but there is a risk of wake-vortex encounters from uncertainty in touchdown points.

When the crossing point is further down the runway from touchdown, ATC would have to control the flare, braking and deceleration of the landing aircraft to influence the time of reaching the crossing point. This seems to be unrealistic even for highly automated aircraft where the braking performance can be prescheduled.

However, when the crossing point is far enough down the runway it should be possible to extend the weather conditions under which "Hold Short" landing operations can occur. This procedure effectively uncrosses the landing paths by declaring one of the landing runways to "end" short of the other when it is felt that sufficient landing distance is available. This could be supplemented by an angled exit parallel to the other runway before the crossing point if the runways converge at an angle of 30 degrees or less as a "safety valve" whenever errors occurred at critical times.

The critical issue for Hold Short IMC operations would be the provision of safe missed-approach procedures for runways with high convergence angles. The probability of potentially-conflicting missed approaches is very small, and good monitoring of approach aircraft can determine when such situations might be occurring. If aircraft on approach were in such a position that there would be a problem if they were both to call for simultaneous missed approaches, then one or the other could be deliberately called into an early missed approach. This would be a rare occurrence, particularly if runway operations were scheduled to avoid it, supported by improved control over merge spacing and groundspeeds on approach.

1.7 Summary - Improving the Operational Capacity of Runway Systems

This critical review is the first step under a research grant, which has the objective of determining ways in which advanced technology can contribute to increasing the operational capacity of runway systems, by creating safe new ATC procedures and reducing separation criteria. In this section, we shall summarize the various approaches identified in the body of this report. It forms a starting point for further research.

1.7.1 Increasing the Approach Capacity of a Single Runway

The most critical capacity at major airports is the approach capacity, since it limits the landing rate. There are several ways to increase approach capacity if we assume advanced technologies for aircraft flight control, flight displays, digital communications, improved surveillance and tracking, and improved ground sector displays with automation.

1.7.1.1 Improved ATC Displays to Reduce Approach Spacing Criteria

Current approach criteria are distance-based and specified only to the nearest nautical mile, so that they can be easily used by radar controllers. The wake vortex criteria are similarly kept simple, by creating only three classes of aircraft and ignoring actual landing weight and approach airspeed. It would be more efficient to switch to time-based separation criteria, where the appropriate distance separation is displayed to the controller for each pair of aircraft.

Much more complex criteria can then be contemplated which depend on ceiling and visibility, winds and atmospheric stability, and the expected approach speeds. For the closing cases, where there is no intervening takeoff scheduled, it is possible to display for the spacing controller the distance separation at merge, which will produce a desired time interval at touchdown (either the expected landing occupancy time, or the required wake vortex dissipation time, or the desired interval between successive missed approaches). For the opening cases, the separation at merge is critical, and there are various ways of safely achieving reduced in-trail separation in the merge area. Slower aircraft should be scheduled or metered to merge as close to the outer marker as possible, and vectored using vertical separation to achieve a reduced initial in-trail spacing.

1.7.1.2 Automated Display of Vectoring Cues to Achieve Better Merge Spacing

In the discussion of approach capacity, there was a buffer ΔSE_{12} which was required to avoid a high violation rate of separation criteria. The spacing errors can be reduced for any merge controller by creating a set of "prompts" or "cues" to assist in calling vectors and speed changes in the merge spacing process. Automated spacing can also be developed with digital datalink and advanced flight control systems.

1.7.1.3 Automatic Groundspeed Control on Final Approach

In establishing a schedule of runway operations and the resulting desired spacings, another uncertainty which requires a buffer is the actual groundspeed likely to be achieved on final approach. When aircraft are capable of automated 4-D flight, it is possible to specify a desired groundspeed, and to increase the confidence of estimated arrival times at the runway. Such flight on approach needs further detailed investigation to ensure its safety in the presence of micro-bursts. It would give the safe reaction of adding thrust when the headwind is encountered, and reducing thrust when the tailwind is encountered, after the downburst. Such modes of automatic flight need to designate a minimum safe airspeed which would preempt control over groundspeed.

1.7.1.4 Sequencing and Scheduling of Approach Operations

There are capacity benefits to both pure approach operations and mixed operations from scheduling/sequencing which minimizes the occurrence of the larger separations between certain pairs of aircraft on approach. If desired time-based separations are displayed (following Section 1.7.1.1 above), it is a small extension to begin scheduling the desired positions of each aircraft on the extended centerline (or nominal 3-D STAR). This process also meters the arrival flow of aircraft to ensure that delays are not incurred early in the metering process, which causes inefficient gaps to occur in the arrival flow at the merge area.

1.7.1.5 Split Approach Paths

Although introduced in the section of the report dealing with close parallel runway operations, the operation of split approach paths will also significantly increase the approach capacity of a single runway. The capacity increases are a result of providing three initial merge areas and reducing the common path length to roughly one mile. The geometry is shown in Figure 1.5. Note that an advanced ATC display is required to assist the ATC controller in spacing. A coordinated display of desired positions at merge can be shown to coordinate all three initial merge paths.

1.7.2 Increasing the Capacity of Mixed Runway Operations

Inserting departures into the landing flows makes maximum use of the runway system, although controllers wish to avoid such mixed operations due to their complexity and requirements for coordination. There are a number of ways to ease this complexity, and to create higher capacity departure operations during climbout.

1.7.2.1 Improved ATC Displays for Timed Runway Operations

The insertion of departures depends on a complex relationship between operational events, which can be easily resolved and displayed to the Tower Controller. The touchdown arrival time can be estimated from radar tracking of the next approach aircraft. A complex set of relationships between departures on various SIDs (or potential missed approach and departure) on crossing, parallel, or the same runway, can be resolved and displayed as a "Red, Yellow, Green" color-coded tag. The Tower Controller would have to enter touchdown, start of roll, and runway exit times. The benefits would be time-efficient decisions in the mixed operation of the runway system.

1.7.2.2 Improved Separation Criteria for Runway Operations

With improved ability to provide ELOT, ETOT values based on aircraft type and current wind, and time-based wake vortex criteria, a set of more complex, efficient separation criteria can be created. Knowledge about divergent departures on SIDS (or Missed Approach Procedures) can be used to reduce current departure criteria. The current runway occupancy criteria are based on a simple categorization of aircraft and rough measures of one-half, three-quarters, and one nautical mile separations along the runway. These criteria for dual occupancy of the runway can be time-based, dependent on the expected performance of each type in terms of approach speed, exit geometry, wind speed, and departure speed.

1.7.2.3 Automatic Flight Along Complex Departure Routings

The ability of advanced flight control systems to accept and conform to complex 3-D or 4-D departure routings can greatly improve departure sector capabilities. Similar effects arise from the capability to fly complex Missed Approach Paths with good conformance. Lateral separation can be provided by creating left or right offsets to the current SIDs. With digital communications, the controller can create "ad hoc" SIDs, and transmit them to the AFCS for concurrence by the aircrew.

1.7.2.4 Scheduling and Sequencing of Runway Operations

The scheduling of both takeoffs and landings on a mixed runway operation offers further efficiencies by ensuring that there are minimal gaps in runway occupancy at busy times.

1.7.3 Improving the Capacity of Multiple Runway Operations

At major airports, the high level of traffic demands that more than one runway be used at peak times. To ease coordination problems, controllers seek to establish independent operation of parallel, or crossing runways for landings or takeoffs. Most of the improvements discussed previously also contribute to establishing an efficient multiple runway operation, but there are two particular operations identified in this report.

1.7.3.1 Split Approaches to Close Parallel Runways

By separating the merge areas for two approach paths, the problems of feeding close parallel approaches are avoided. Independent runway operations down to the 2500 feet lateral separation required for wake vortex considerations can thus be provided with its doubling of landing rates. There are a number of interesting problems in aircraft flight control, pilot handling, etc., associated with the gentle turn to runway direction after breakout to VMC under poor visibility, night operations, with the possibility of a missed approach, etc., which need to be addressed. Such an operation has been in effect at Washington National for many years, using current ATC and aircraft equipment.

1.7.3.2 Hold Short Operations on Crossing Runways

Today, when ceiling and visibility permit missed approaches to be executed in VMC, operations which impose "hold short" conditions on landing aircraft are authorized. By scheduling runway operations, and by providing missed approach procedures which diverge from the other runway, it is possible to extend these operations to much lower ceilings and visibilities. This extension would provide multiple approaches to many major airports at periods when they need them, and is similar to the prior proposal for close parallel runways with angled approaches. The critical operation in both cases is simultaneous missed approaches from a point near (or after) breakout to visual conditions.

PART 2. THE DEVELOPMENT OF RISK-BASED SEPARATION CRITERIA FOR ATC OPERATIONS

2.1 Introduction

Part 2 of this report discusses the problems involved in establishing efficient separation criteria appropriate to various air traffic situations. These criteria necessarily involve a tradeoff between safety and capacity -- if they are reduced, then capacity is increased and safety is decreased. However, if a "Target Level of Safety" (TLS) can be established which sets a limit for the risk incurred in any encounter between aircraft, then "efficient" separation criteria are those which achieve a TLS with minimal values of separation and therefore provide maximum capacity to ATC operations. There is a need for research on the process by which these separation criteria are established.

We shall discuss a rational approach to establishing a structure which allows the analysis of separation criteria for all general ATC operations, and for runway system operations in particular. Hopefully, this structure can be used to establish separation criteria which achieve a TLS under various traffic encounter situations, and which then allows these criteria to be a function of advanced technology in surveillance, communications, and flight guidance. These advanced separation criteria will be more complex, expressed perhaps as particular to each pair of aircraft of known capabilities, or each particular traffic situation, weather situation, etc., and may be expressed in terms of time instead of radar distances. With advanced display technology, these more complex, efficient ATC separation criteria become feasible, since the human controllers need not be tasked to remember and apply them.

Advanced technologies should allow a reduction in ATC separation criteria and a corresponding increase in ATC capacity. Improvements in aircraft flight guidance technology improve performance in track keeping and altitude keeping, i.e., the conformance to assigned paths; improvements in surveillance technology provide the ground monitor with better knowledge on current aircraft position, speed, and direction; improvements in communication technology allow faster transfer of information and commands between ground and aircraft. Introducing these advanced technologies into ATC operations will require an investment cost. The benefits to offset their cost can come from increased capacity due to reduced ATC separation criteria if we can establish the links between risk and performance and technology, and use them to establish reduced separation criteria for ATC operations.

2.2 Concepts for ATC Separation -- Hazard, Separation, and Alert Criteria

The purpose of setting separation criteria in ATC operations is to avoid the occurrence of encounters between pairs of aircraft which are judged to be unsafe. These unsafe encounter events can be called hazard events, or near-miss events, or ultimately mid-air collisions. Note that while the ultimate purpose is to prevent collisions between aircraft, a hazard or near-miss is often used to define an "unsafe encounter". A collision is easily defined, but there is a necessary exercise of judgment in establishing hazard criteria for various traffic encounter situations in terms of miss distance, or miss time. Given the definition for "hazard criteria", H, the TLS can then be stated in terms of the average frequency of violation of hazard criteria or the risk of incurring a "hazard event" over the ensemble of a large number of similar traffic encounter situations.

Given H and TLS, there is another set of "separation criteria", S, which guides the establishment of ATC operations and procedures. If these "working criteria" are followed, they should achieve the TLS in terms of risk of hazard events, averaged over a large number of encounters. They are called "working criteria" because they will be violated 50% of the time by small deviations. There is no absolute or inviolate application of S criteria. They are intended to be achieved on average such that TLS is achieved on an average over all similar traffic situations, i.e., the risk of a hazard event is below TLS. It is not an unsafe event if S is violated, as S is roughly an order of magnitude larger than H.

An example of S is the current altitude separations of 500 feet VFR, 1000 feet IFR below Flight Level 290, and 2000 feet for IFR above FL 290. A hazard dimension in the vertical is roughly ±50 feet, and the altitude-keeping performance of aircraft could be taken as ±100 feet at lower altitudes. For jet aircraft, it has been thought that their altitude-keeping performance degrades with altitude such that around FL 290 the value of S should be increased to 2000 feet. (This is currently under review to see if a higher altitude than FL 290 can be safely used). The point is that aircraft flying an airway assigned to adjacent altitudes are violating these altitude separations 50% of the time by small deviations without creating an unsafe event.

At present there is some inconsistency in the U.S. concerning the concept of a working separation criteria. If two aircraft are assigned to fly adjacent parallel routes, co-altitude, under radar control at a spacing corresponding to a radar separation criteria of 3 n. miles, each small violation of 3 n. mile separation would be declared an "Operational Error" which is often considered to be synonymous with "unsafe event" or "hazard". Here we are defining S as a nominal or working separation for ATC operations, expected to be violated 50% of the time, and selected to achieve TLS over an ensemble of similar traffic encounters. It is not a hazardous event if S is violated, but only when H is violated.

There is another type of operational criteria used in monitored traffic situations called "Alert Criteria", A. They are used to provide an alert or warning time to controllers of the predicted violation of either H or S criteria. By projecting the future position of a particular pair of aircraft (usually based on a straight-path projection at current estimated path speed), these criteria are intended to provide the controller with just sufficient time to command a resolution maneuver to avoid violation of H or S. We shall designate these two types of alert criteria as "HA", for Hazard Alert, and "CA", for Conflict Alert. (The future violation of separation criteria is usually called a "conflict".) We are now in a position to develop a structure for risk-based separation criteria for two basic types of traffic situations -- unmonitored and monitored.

2.3 Separation Criteria for Unmonitored Traffic Situations

In the unmonitored situation, aircraft are assigned to a flight plan which is separated from adjacent flight plans by some distance/altitude/time criteria. We shall denote these unmonitored separation criteria as "S_u". They are chosen such that the risk of a hazard is below the TLS. Since there can be no monitoring of the conformance of aircraft to the assigned track, or of the actual separation between aircraft on adjacent tracks, the risk of a hazard occurring depends solely upon the performance of the aircraft in conforming to assigned altitudes, tracks, and times. "Track Wander", or "Flight Technical Error", or "Arrival Time Error" describe the average expected deviation from track, altitude, and time for this particular traffic situation. If the statistics on conformance capabilities of aircraft in the traffic mix are known, the required separation between tracks or altitudes to achieve TLS can be found and stated in terms of some multiple of the average deviations expected.

For example, consider the case of traffic on parallel adjacent tracks at the same altitude. In Figure 2.1, we show three parallel tracks. Aircraft A is proceeding northbound at speed V_A. To its left is aircraft F, proceeding southbound at speed V_F towards a "frontal" encounter with A. To the right is aircraft O, proceeding northward at a speed $V_O > V_A$ towards an overtake encounter with A. The tracks are separated by S_u. We know the track deviation statistics for all aircraft which use these tracks from a long-term data-gathering survey. It is characterized by a probability density function pdf(y) for a crosstrack deviation y, which has a zero mean and a standard deviation σ_y. Assuming the behavior of aircraft are statistically independent, we can derive the pdf (Δ_y/S_u) where Δ_y is the lateral separation between a pair of aircraft given they are nominally separated by S_u. This distribution is also shown in Figure 2.1 for the overtake encounter.

If we define the Hazard criteria, H, to be a circle of radius H around A, then we know the risk that $\Delta_y < H$. It is given by the shaded area under the pdf (Δ_y/S_u) curve when $-H \leq \Delta_y \leq H$. It is approximately $2H \cdot \text{pdf}(0)$ since the slope of the probability curve is very small when pdf(O) is of the order of 10^{-6} or more, and S_u is an order of magnitude larger than $\sigma_{\Delta y}$.

To have a hazard event, the aircraft must also have $\Delta x < H$ at the time when $\Delta_y < H$ (where Δx is the along-track separation). For the overtake encounter, the time of overlap is $2H/(V_O - V_A)$ when $\Delta_x < H$. For the frontal encounter, the overlap time is $2H/(V_F + V_A)$ which generally is smaller in duration than the overtake encounter. Interestingly, this causes the risk of a hazard occurring to be smaller for each frontal encounter, but this is exactly offset by a higher expected rate of occurrence of frontal encounters (which is directly proportional to the relative speeds), so that the hazard risk overall will be identical if S_u is the same for frontal and overtake cases and traffic densities are uniform.

The desired separation S_u is chosen to achieve TLS. However, it can be difficult to obtain statistical confidence in this methodology since TLS is very small, and a large number of real world observations are required to define the tails of the pdf(Δ_y) for all aircraft in the expected traffic mix. This observation activity could take a number of years during which the track-keeping performance of aircraft and the mix of aircraft could be changing. The observed track-keeping performance is the result of various error sources -- wind fluctuations, navigation equipment errors, guidance laws, etc. The "normal" performance could be predicted by analytical methods, given knowledge of these error sources, but there are also some "abnormal" sources of error from equipment failure or human failure (blunders -- e.g., where the pilot or controller selects the wrong path). Since S_u is large, the tails of pdf (Δ_y) may be dominated by these abnormal modes rather than the normal performance of the flight guidance systems.

The value of S_u required to reach a desired TLS in Figure 2.1 depends on the statistical evidence on track-keeping. If this data is dominated by the normal mode, then improvements in lateral track-keeping system performance in the mix of aircraft will allow proportional reduction in S_u. If the mix of aircraft can be classified into groups with known levels of performance, then reduced values of S_u could be applied between pairs of aircraft belonging to groups with higher performance levels. This creates a complex set of S_u values applicable under particular circumstances which could be displayed to the ATC controller as they occur.

If the data is dominated by the abnormal modes, then improvements in S_u must come from the ability to reduce abnormal errors by improving equipment maintenance or improving man-machine relationships, or to provide a secondary check for abnormal errors (e.g. from ground surveillance in monitored traffic situations).

2.4 Separation Criteria for Monitored Traffic Situations

For monitored traffic, aircraft are assigned to a track and altitude, and then their actual position and altitude and separation from another aircraft is monitored. If a specific pair of proximate aircraft (called an "encounter pair") is observed to be closing on hazard or separation criteria, corrective resolution commands can be issued by the controller. Thus, we have monitored separation criteria, S_m, applicable in real time to each individual pair of aircraft, not average criteria for the ensemble of all traffic in some situation. Now there are several factors, normal and abnormal, which determine the values of such separation criteria, S_m.

First, the expected conformance of aircraft to their assigned tracks and altitudes is still a factor. While the actual deviation may be observed by the controller, there is still an expectation that the aircraft will conform with a high degree of reliability to its intended flight path without any sudden or large deviation. Second, the accuracy and time response of the surveillance system is now a factor -- both in position/altitude as well as rates of position/altitude. The controller needs changes in altitude, speed, and direction to monitor closures between the encounter pair.

The third normal factor in setting separation criteria for monitored traffic may be called the "Encounter Resolution Performance" of the system. This is determined by the combined encounter resolution response time of the ground monitoring system, air-ground communication system, and the aircraft flight control system in performing the following stages of Encounter Resolution:

1) Encounter Prediction and Declaration
2) Generation of Resolution Commands
3) Transmission of Commands to Aircraft
4) Acceptance and Acknowledgment of Commands by Aircraft
5) Execution of Resolution Commands

All of the above stages require time to accomplish, and as a result, separation criteria for monitored traffic are really determined in the time dimension, although there are corresponding distance values. With good response time in Encounter Resolution, the time values for alert criteria can be made small.

In the monitored traffic situation, there are new sources of abnormal error. The effects of airborne equipment failure or pilot blunders for abnormal deviations can be cross-checked by a ground monitoring system, but now there can be abnormal errors in the Encounter Resolution, such as issuance of wrong, insufficient, or delayed resolution commands by the ground, and similar errors in execution of the resolution commands by the aircrew.

For traffic situations where normal error sources dominate, it is expected that S_m can be smaller than S_u, since the provision of a "Conflict Alert" (or "Separation Alert") should ensure that the aircraft pair are in a resolution maneuver before S_m occurs. The minimum alert time is the "evasive" resolution time, although it is possible to resolve encounters earlier with a "soft" alert even when the probability of a true conflict is low. This non-evasive alert is not in use currently. If the alert time were constant, the evasive alert distances are a function of relative speeds and directions in the encounter. As shown in Figure 2.2, the CA boundary exceeds the S_m boundary and extends much further in front of an aircraft A than behind it; i.e., a frontal encounter with its higher relative speeds requires more distance for the same alert time whereas an overtake encounter can be much closer before the resolution is initiated. (For example, for a head-on encounter between two aircraft both at 540 kts speed, an alert boundary of 60 seconds requires 18 n. miles whereas for an overtake encounter at 30 Kts, 60 seconds requires only 0.5n. miles.)

Evasive resolution maneuvers in the horizontal plane are shown in Figure 2.2 where it can be seen that they may require slightly varying times to reach S_m for different angles of encounter. However, the evasive resolution maneuver also could be in the vertical plane where a constant time independent of direction is required. The goal of the evasive resolution maneuver is to achieve S_m on average over a large number of similar resolutions, such that the risk of a hazard during the resolution meets TLS. Once again we would expect S_m to be violated by small amounts roughly 50% of the time. The statistical basis for establishing confidence in S_m may be impossible to provide from surveying operational statistics given the rare occurrence of such encounters. It is possible to simulate the resolution performance, given a description of normal error sources.

An example of this type of traffic situation and structure of separation criteria exists in the "Conflict Alert" and "Minimum Safe Altitude Warning" (MSAW) systems currently in operation with the NAS and ARTS systems. However, the underlying rationale for these systems as outlined above does not appear to exist since there is no TLS or rationalization for the S_m values used in these systems. For the ARTS III Conflict Alert processing, S_m values of 1.2 n. miles laterally and 300 feet separation in altitude have been selected with a time alert of 25 seconds. It is not known how these values were selected, and they co-exist with larger radar separation criteria.

When the monitored traffic is assigned to follow parallel paths at a separation S_m, the situation creates another alert criterion, HA, called a "Hazard Alert". This allows S_m to be less than S_u by introducing a control intervention called a "Hazard Resolution Command", which reduces the probability of a collision back to the desired TLS. Although the time values for evasive Hazard and Conflict Alerts may be similar, the nominal flight along parallel paths in this traffic situtión allows an expectation that cross-track relative velocities will be small. This reduces the corresponding distances significantly, such that HA boundaries are smaller than S_m boundaries. It is still expected that S_m will be violated roughly one-half the time by small deviations, so that HA must be far enough away from S_m to keep the hazard alarm rate small enough to be acceptable.

The Hazard Alert criteria is based upon information on current separation distances and separation rates of adjacent pairs of aircraft. These monitoring data generally are obtained from the tracking system of a ground surveillance system and are strongly dependent upon surveillance precision and update rate. Estimates of cross-track position and speeds can be greatly improved if onboard data on speed and heading (or heading rate) are downlinked to the ground. Similarly, smaller S_m and Hazard Alert criteria, HA, can be achieved if communication times for Hazard Resolution commands are reduced by using datalink systems, and a standard resolution maneuver is preprogrammed to be executed automatically with minimum delay by automatic flight control systems.

As with the unmonitored traffic situation, the normal performance of the aircraft guidance system (which provides an analytical basis for predicting cross-track deviations and alarm rates) is not sufficient for the monitored traffic situation, since there is also the possibility of "abnormal" performance. Such possibilities as guidance system malfunction, pilot blunders in setting or maintaining inputs to the guidance system, errors in issuing or receiving or executing resolution commands, etc., introduce another set of rare events whose probability must be estimated if we are to establish S_m and HA criteria which meet a TLS for these parallel traffic operations. If normal performance is improved, these abnormal events may dominate.

A schematic representation of separation criteria for parallel traffic operations is shown in Figure 2.3. The evasive HA boundary for aircraft A is displaced in front of it due to the effect of relative speeds for aircraft F (which provides a frontal encounter on the left path) and for aircraft O (which provides an overtake encounter on the right path). To provide a low hazard-alarm rate, a hazard buffer is used whose size depends on the normal track-keeping performance of the aircraft. This hazard buffer is added to the critical alert boundary values for the frontal and overtake encounters to establish S_{CF} and S_{CO}, the controlled separation criteria for parallel frontal and overtake encounters. These take different values because the critical alert boundary values occur before passage for the frontal case, where the HA boundary is further from the track of aircraft A. The fact that the relative speeds will be higher for parallel frontal operations requires more lateral separation to ensure sufficient time for hazard resolution; or vice versa, as the relative overtake speeds become smaller, the lateral separation criteria for parallel overtake operations can be reduced since there is more time to execute hazard resolution. This explains the lower lateral separations for same direction close parallel approaches in current operations.

The prime example of this traffic situation (parallel overtake operations) and reduced separation criteria is the current IFR independent operation of dual parallel ILS approaches. Once established on the ILS centerline, aircraft are allowed to fly independently under IMC at a lateral spacing of only 4300 feet. A NTZ (No Transgression Zone) is created between the ILS centerlines to serve as the HA boundary, and must be at least 2000 feet wide, or at least 3150 feet from the other centerline. If ATC controllers monitoring parallel approaches observe a transgression by one aircraft, they intervene to provide an alert to that aircraft, and to send a resolution command to any aircraft which might be on the opposite centerline.

There is an assumption in this resolution procedure that an abnormal event has occurred for the transgressing aircraft and that the resolution command should be sent to the aircraft whose performance seems normal. Notice that an alert boundary has been established for the opposite centerline, independent of whether or not an aircraft is actually there (which allows independent operation of the two approach paths). There is a high probability that no aircraft is actually there when a significant deviation occurs which affects the achieved TLS.

Under these conditions, parallel flight in IMC may be planned at a lateral separation of 4300 feet, but in VMC, these operations are allowed down to 700 feet lateral separation with the pilots responsible for safe separation. Yet in other traffic situations (including the merge operations just prior to the parallel ILS operation), aircraft under radar control must be separated by 18,000 feet (3 n. miles). The current use of the simple 3 or 5 n. mile radar separations for general monitored traffic situations is extremely inefficient. There are many occasions when their violation does not result in any risk whatsoever. For example, Figure 2.4 shows a situation where a descending aircraft entered the 3 n. mile, ±1000-foot disk surrounding another aircraft at a point 2 n. miles behind and headed away from that aircraft. At the time such a violation of S_m is declared with the implication that this is a hazard or unsafe event, there is no possible way in which a collision or near-miss can occur.

Comparison between these unmonitored and monitored situations shows that separation criteria have been reduced whenever improved system performance in flight guidance, communication, and surveillance are present in the traffic situation. Advanced technology in the form of 2-D, 3-D, and 4-D automatic guidance of aircraft, or digital communication of alerts and commands, or advanced computer displays, or improved tracking and surveillance of aircraft, which provide further improvements in performance certainly have the potential to create new traffic operations with separation criteria reduced below current values.

2.5 Summary - Factors in Establishing ATC Separation Criteria

From the above sections, we can make the following observations about establishing ATC separation criteria:

1) Current separation criteria vary widely for different traffic situations. For example, lateral separation between aircraft varies from 30,000 feet for radar separation more than 40 n. miles from the radar, or 18,000 feet when less than 40 n. miles, to 4300 feet for independent parallel flight in IMC on parallel ILS paths, or to 700 feet for visual parallel flight on runway approach; or for vertical separation, from 2000 feet above Flight Level 290, to 1000 feet in IMC, to 500 feet in visual conditions. These variations implicitly recognize that safety is dependent upon the traffic situation and the performance of flight guidance, surveillance, and communication systems which determine the degree of controllability over aircraft paths.

2) Separation criteria should be working criteria which are violated to a small degree roughly 50% of the time. Their value is set to provide a Target Level of Safety in avoiding an unsafe event called a Hazard or

Collision. When aircraft are being monitored, it is possible to introduce Alert criteria which provide warning of potential violations of Hazard and Separation criteria by any individual pair of aircraft. This allows monitored separation criteria to be smaller than unmonitored separation criteria. Alert criteria are given in the time dimension and are dependent on the geometry and speeds of the encounter. In-trail and parallel traffic operations under monitored conditions can have reduced separation criteria measured in distance.

3) Because Alert criteria are expressed in time, it is efficient to express monitored separation criteria in the time dimension also. While this makes distance criteria dependent upon the speeds of aircraft, it is possible to use current display technology to provide a graphic presentation of the appropriate distance to ATC controllers or aircrew for a particular traffic situation. Given: 1) the capabilities of the flight guidance systems to operate coupled automatically to 2-D, 3-D, or 4-D paths; 2) the capabilities of the surveillance system, (perhaps aided by downlinked information from the aircraft flight guidance system) to track the the position/altitude, and to provide estimates of their rates without excessive delay; 3) the capabilities of digital communications to reduce the time for transmission of control commands; and finally 4) the capability of advanced flight guidance systems to execute hazard resolution commands promptly and correctly, it is feasible to create more-complex, efficient statements of safe separation criteria which are applicable to each individual pair of aircraft. This allows reduced separations in each situation, rather than basing separations on the worst case of the traffic situation and aircraft mix of capabilities.

2.6 Reducing ATC Separation Criteria Which Increase Runway Capacity

From the discussions in Part 1 of this report, it was suggested briefly that reductions in the following ATC separation criteria will provide improvement in the operational capacity of runway systems at major airports. Now we will discuss in further detail those reductions, trying to suggest what value might be achieved and showing how improved performance from advanced technology might justify them.

2.6.1 Reduction in In-Trail Separations on Approach

Currently, these separations are expressed as 3,4,5, and 6 n. miles depending on the type of aircraft. Data from hundreds of thousands of wake vortex observations are available to provide statistics on the persistence of the wake vortex behind particular aircraft under particular meteorological conditions in terms of wind and atmospheric stability. This persistence is measured in time - for example, the longest observations of wake vortex persistence are 112 seconds behind a B-747, and 87 seconds behind a B-727 (see Reference 1). There may be sufficient statistics to establish a TLS of wake vortex encounter based on maintaining a time separation between aircraft at all points on approach. Here we suggest that 90 seconds behind a Large aircraft and 120 seconds behind a Heavy aircraft can be taken as a potential value for a safe longitudinal time separations on approach.

It is also possible to provide vertical separation from the wake vortex during approach operations by requiring aircraft to be automatically coupled to the initial approach altitude and the glide slope. If altitude conformance can be maintained within 50-75 feet (1σ) at these low altitudes, and if longitudinal time spacings are of the order of 90 seconds, the wake vortex is displaced below the nominal approach altitudes by several hundred feet except near the ground. For the case of a slow, small aircraft following a large, faster aircraft, where minimum separations occur at merge and not at the runway, this means that longitudinal separation from the wake vortex in the merge area can be reduced if good conformance to nominal altitudes can be achieved by both aircraft.

If both approach aircraft are capable of 4-D flight, which implies the ability to maintain a constant groundspeed in the face of varying winds as altitudes change, then their ability to conform to a desired constant groundspeed is also a factor in establishing longitudinal time separations on approach. The buffer due to speed error can be reduced for the closing case where the faster aircraft catches up to the preceding aircraft at the runway, and in fact, speed control could be used to reduce any spacing errors by commanding the desired groundspeed on approach. As a goal, we suggest that the combined buffer for speed and spacing errors be taken as 5 seconds.

Given a long runway, it may be possible to specify a common groundspeed on approach for successive 4-D-capable aircraft which would maintain a constant longitudinal separation during the approach. With close monitoring of position and speed, ground control could request small changes in groundspeed to maintain these longitudinal time separations to within, say ± 5 seconds (1σ) to be consistent with the combined buffer given above and could provide a hazard alert which triggers an automatic hazard resolution/missed approach procedure whenever they are too close. In proposing 90 and 120 seconds as S_m for these cases, it is presumed that the availability of automatic evasive missed approach capability (EMAP), and digital communications with the particular pair of aircraft will allow evasive hazard alert criteria, HA, of the order of 30 seconds.

With a higher scan rate from surveillance radar, or with downlinking of groundspeed/airspeed data from the aircraft, the Hazard Alert can be expessed as "time to zero spacing" using up-to-date measurements of longitudinal spacings and groundspeeds. If violated, digital communications can transmit the evasive missed approach command to the aircraft with little delay after displaying it to the controller monitoring the in-trail operations. With cockpit display of the alert, the EMAP can be automatically executed after the pilot accepts the command. The EMAP is preprogrammed before initiating the approach with the controller specifying alternative EMAP paths for successive aircraft to ensure initial separation between two successive commands for EMAP should that event occur.

It is easy to establish these values as goals and to indicate the requisite performance. Demonstration of in-trail operations at these levels of separation will require extensive research and flight test to gain acceptance by the aviation community worldwide. In the next part of this report, we shall show the benefits of such reductions in in-trail separations in increasing the capacity at Denver and Boston.

2.6.2 Application of Vertical Separation at Merge

There is a problem in merging a slower aircraft on approach behind a faster aircraft. This should be accomplished close-in to avoid a large gap at landing, and this generally will result in the faster aircraft passing directly in front of the slower aircraft at minimal separation. It is possible to apply vertical separation between the aircraft to ensure safety during the merge maneuver, but if the current separation of 1000 feet is used, there may not be sufficient time for the second slower aircraft to descend and capture the initial approach altitude for a standard ILS approach, especially if current radar separation criteria are applied. These would require 3 n. miles separation to open up before allowing the slower aircraft to descend.

Given good surveillance and tracking to ensure that the faster aircraft has passed and to confirm that the first aircraft is truly faster, it is possible to clear the slower aircraft down to co-altitude after some smaller separation (say 0.5 n. miles). It would be necessary to command each aircraft to maintain its speed, and to avoid garbling of the beacon radar returns by using Mode S technology.

But it is also reasonable to consider using only 500 feet vertical separation in IMC at these low altitudes if both aircraft are altitude coupled, established at their assigned altitudes, and have confirmed a common altimeter setting. This would ease the problem of getting the slower aircraft under the ILS glideslope before acquisition at the Outer Marker, or alternatively the slower aircraft could remain at its 500 foot higher altitude and intercept the glide slope early at about 1.5 n. miles before the Outer Marker. These procedures create a potential wake vortex encounter for the next aircraft after the slower aircraft, but if the next aircraft is faster, it will be spaced to catch up to the slower aircraft at the runway, and will have greater spacing at the Outer Marker. If the next aircraft is slower, it may also be assigned to a level either 500 or 1000 feet higher than the initial approach altitude depending upon its speed difference from the first slow aircraft. This may require good planning of runway operations and automated sequencing and spacing to get the slower aircraft inserted as desired into the approach flow.

2.6.3 Reduced Separation for Close, Parallel Approach Operations

The current minimum lateral separations of 4300 feet for independent parallel ILS approaches under IMC is currently under review to see if the lateral separation can be reduced to around 3000 feet. The proposed methods used to obtain this reduction are some of those indicated by this part of our study: i.e., insisting on auto-coupling for all aircraft, and monitoring with a radar surveillance system of higher scan rate and improved tracking capability to improve alert capability.

Dependent parallel ILS operations in IMC are currently allowed to 2500 feet with a 2 n. mile diagonal separation. The lateral displacement of the wake vortex at touchdown under gentle crosswinds prevents further reduction since there have been some observations close to this distance (see Reference 1). For visual parallel approaches, the required lateral separation is only 700 feet currently with the caveat against overtake by heavy aircraft. At Denver and Los Angeles, this has led to the use of "visual paired approach" procedures where aircraft are deliberately vectored to a visual intercept or merge, from whence they fly alongside each other at the same speed to a "formation" touchdown. This avoids wake vortex risks since there is no time for the vortices to reach the other paired aircraft. The next pair of landings will have normal wake vortex separation criteria. At these airports, pilots are responsible for maintaining lateral separation from the other paired aircraft by visual means during the merge and approach. With the visual paired approach procedure, the landing capacity of the close parallel runways is exactly double the capacity of a single runway.

Note that it is almost impossible for an aircraft deviating from a paired parallel position to collide with its opposite aircraft unless it increases its groundspeed/airspeed. This is not true of alternating parallel approach procedures where an aircraft is in jeopardy from aircraft on the opposite centerline which are slightly ahead of it. Although not obvious at first glance, paired approach procedures offer both higher capacity and increased safety from collision or wake vortex encounters when compared to alternating or independent operation procedures.

If we consider using advanced technology to reduce the separation for close parallel approaches, the critical criteria is the lateral separation which can be safely established for aircraft flying parallel approaches in coupled flight. If this can be less than 2500 feet, then paired approach procedures are necessary to avoid wake vortex considerations at touchdown. If not, then independent parallel approaches becomes the objective between 4300 and 2500 feet.

In both cases, the critical lateral separation criteria may be established by the abnormal behavior of aircraft, pilots, and equipment. If so, then the Hazard Alert performance is critical for detecting the abnormal deviation from centerline, and in transmitting the resolution command, for quick execution of an automatic evasive missed approach procedure (EMAP) away from the other centerline, or away from the projected position/altitude of the deviant aircraft. With digital communication, the resolution command can be variable depending upon the ground's knowledge of the deviant path, displayed in simple form for acceptance by the pilot, and automatically inserted into the flight control system for execution.

With advanced technology, it may be possible to consider "non-visual paired approaches" for dependent operation of close parallel runways at spacings less than 2500 feet. This provides approximately a 30% capacity gain over the current requirements for "alternating approaches" of 2 n. miles diagonal and normal wake vortex separation between aircraft on the same centerline (e.g. at 2500 feet, the 2 n. mile diagonal separation requires 3.86 n. miles between aircraft on the same centerline instead of 3 n. miles). The merge operation in IMC would require vertical separation of 500 feet (if coupled) and perhaps an automated intercept procedure to assist controllers in achieving the "paired" position alongside each other. When both paired aircraft have acquired their centerlines and are stabilized in automatic coupled flight opposite each other along their centerlines, at the same speed, the higher aircraft could then be cleared to descend to the initial approach altitude, or could remain 500 feet higher until glide slope intercept.

The ability to conduct non-visual paired approach procedures requires significant research to establish the monitored separation criteria S_m as a function of the performance of the various advanced technologies. With a mix of performance capabilities in the landing aircraft, it may be difficult to have a simultaneous pair of landing aircraft equipped to perform EMAP unless some form of automatic runway scheduling can be provided, or a substantial percentage of the landing aircraft have this capability. Rather than expose aircraft to the risk of close parallel operations throughout a complete approach, it may be desirable to provide split, angled approach paths which merge after visual conditions are achieved, as discussed later.

2.6.4 Lateral Offset Separation for Departure Operations

There are capacity and workload advantages in being able to provide a lateral offset to Standard Instrument Departure (SID) paths for successive departures. Aircraft of varying weight and climb performance may pass each other while performing the SID. If it is possible to fly the SID with an advanced flight control system which ensures lateral conformance within 600 feet, (1σ), then alternative SID paths with lateral spacing of $\pm$ 1 n. miles may be established, and assigned prior to takeoff. This would match the $\pm$ 1 n. mile separation currently used for 15^o divergent path departures. This would allow reduced takeoff intervals, and provide the departure controllers with a safe initial flow of departure aircraft.

Controllers may desire to deviate from the SID later in the departure process as desired for efficiency or other reasons. The values of 600 feet and 1 n. mile are typical of values which might meet a given TLS. The alternate SID paths could be simply labelled L (left), R (right), and then any lateral offset (measured in feet) could be used to achieve TLS for a specified conformance capability of the ASID (Automatic SID) mode of the flight control system. The deviations will depend on wind strength and variations, and the complexity of the SID paths in terms of size of angular turns, length of straight segments, source of position information, etc. Flight tests of automatic SID functions of an advanced flight control system are necessary to demonstrate normal performance on the order of 600 feet.

PART 3. ESTIMATION OF CAPACITY BENEFITS FROM ADVANCED TERMINAL AREA OPERATIONS - DENVER AND BOSTON

3.1 Introduction

In this section we report on the analysis of the capacity of two of the principal airports in the United States; Denver's Stapleton International Airport (DEN) and Boston's Logan International Airport (BOS). These are, respectively, the sixth and tenth busiest airports in the United States with respect to the number of passengers moved through them in 1984 and both rank among the 15 busiest in the world, as well.

The purposes of the section are several. First, to illustrate through two examples, the process of performing a complete capacity analysis of an airport, taking into consideration all the possible runway configurations, weather conditions, traffic mix, rules on runway usability, etc. Second, to introduce the important concept of the "Capacity Coverage Chart" (CCC), a concept that allows one to summarize the capacity characteristics of an airport in a manner useful to airport and ATC planners and administrators. Finally, to draw some conclusions regarding the capacity needs of the two specific airports examined and the most promising ways for satisfying these needs.

It should be emphasized that we deal here only with airside capacity issues and specifically with issues regarding runway capacity. While at BOS the runway capacity is undoubtedly the determinant of the overall airside[1] capacity (i.e., the runways constitute the principal airside "bottleneck" of the airport) it was suggested to us that at DEN parts of the gate/apron system may also be inadequate and impose their own limitations on airside capacity. However, this last question was beyond the scope of this research.

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[1]It has become quite apparent recently that the landside capacity of Logan Airport may currently be less than the airside capacity. This is primarily due to the deficiencies of the parkirg and road-access systems.

The rest of this section is organized as follows. We first present, in considerable detail, the approach used for the capacity analysis in general form. We then discusses that analysis and the derivation of the current capacity coverage chart for DEN. Subsequently, we give a summary (since the steps are entirely analogous to those for DEN) of the corresponding work for BOS. In each case, a last subsection draws some conclusions with respect to current capacity at DEN and BOS individually.

Finally, a last section introduces some of the advanced ATC procedures and reduced separation criteria which have been discussed in Parts 1 and 2 to demonstrate their potential benefits. This demonstrates one of the purposes of the capacity coverage chart - to ensure that particular improvements at an airport are not dominated by other operations, i.e., to identify which new ATC procedures pay off at the airport by showing their annual or seasonal contribution in terms of increased operations per hour by some percentage of time.

3.2 The Capacity Coverage Approach for Airport Capacity Analysis

3.2.1 Description of the Procedure

It is important to realize at the outset that the capacity of an airport is <u>not</u> constant over time. "Capacity" in this context-and throughout this report-refers to the hourly "saturation" (or "maximum throughput") capacity of the airport, i.e. the number of operations that can be conducted during an hour in the presence of <u>continuous demand</u> and without violating air traffic control separation requirements. In light of this definition it is clear that airport capacity during any given hour is a function of the following:

- runway configuration (i.e., assignment of takeoff/landing operations to runways)
- weather and wind conditions
- aircraft mix

- operations ratio (percentage of landings and percentage of take-offs)
- aircraft-to-runway assignment patterns

Because all of the above parameters that affect airport capacity are variable and some may change randomly, hourly capacity itself is a random variable. Therefore the long-term average value of the hourly capacity is used as a proxy value for this random variable. This long-term average value must be estimated for each given set of the above parameters.

The procedure to be used in a capacity analysis of an airport follows directly from the above observations and definitions. It can be summarized as a five-step process. The first three steps, involve case-identification (or "input preparation"); the last two steps are computational.

Step 1: Obtain weather/wind related information relevant to the airport. This means:

(i) identification of the various weather (i.e. ceiling/visibility) categories corresponding to existing or potential operational runway configurations and terminal area approach procedures; (these are designated VFR-1, VFR-2, IFR-1, IFR2, IFR-3, IFR-4, here for Boston);

(ii) rules on crosswind and tailwind tolerances for runway operations; and

(iii) annual or seasonal airport weather/wind roses for each category of weather identified under (i) above.

Step 2: Identify all runway configurations that can be used in each weather category as well as associated ATC procedures and separation requirements. The sets of runway configurations that are available in each weather category may obviously be different. For example, a runway which can be used for landings under VMC (Visual Meterological Conditions) weather conditions may not be usable for landings under IMC (Instrument Meteorological Conditions) weather, due to insufficient instrumentation. Similarly, the ATC approach procedures and requirements may also change with the weather. Two runways which can be operated independently in VMC weather may become dependent under IMC.

Step 3: Identify the traffic mix and aircraft-to-runway assignment patterns for each of the runway configurations of Step 2. Clearly, aircraft-to-runway and operations-to-runway assignment patterns will vary with runway configuration in use and prevailing wind/weather combination. For example, a runway which is used only for turbo-jet landings under one particular configuration may be used for all types of operations and all types of aircraft under another. Perhaps less obviously, the overall aircraft mix at a major airport may vary as well with weather/wind conditions. For example, the percentage of general aviation aircraft in the mix (especially that of single-engine props) may decline significantly in IFR weather.

Step 4: For each of the runway configurations of Step 2 and its associated mix and assignment patterns, compute the airport's capacity. In all but the simplest cases, a computer program will probably be necessary at this step. Available programs can be either analytical/mathematical models or simulations and can cover a wide range of capabilities, complexity and sophistication. The FAA Airfield Capacity Model and the FAA Airfield Simulation Model are well-known ones that can be used for this purpose. Several airport consulting companies have developed their own proprietary models, as well. In the case of the BOS capacity analysis reported below, the analytical model RUNCAP and the simulation model RUNSIM, both developed at MIT, were used.

Step 5: Rank the runway configurations in order of decreasing capacity, compute the marginal availability of each configuration and draw the capacity coverage chart (CCC) for the airport. The details of Step 5, including a discussion of the CCC - the ultimate output of a capacity analysis - are presented below.

3.2.2 The Capacity Coverage Chart (CCC)

The CCC is a procedure, developed recently at MIT, for the purpose of summarizing the capacity characteristics of an airport in a manner useful to airport and ATC operators, planners, and administrators. It is based on the observation that during periods of high demand, the air traffic controllers will use the available runway configuration which offers the highest capacity under the prevailing weather/wind combination. This implies the following: Assume that n possible runway configurations exist at an airport (these n configurations would be identified under Step 2 of the procedure outlined in the preceding subsection). Assume also that these configurations have been ranked in order of decreasing capacity (based on the results of Step 4 of our procedure) and labeled {1, 2, ..., n}, with configuration 1 being the configuration with the highest capacity and n the configuration with the lowest. It then follows from our earlier observation that, at least during high demand periods and for any given prevailing weather/wind combination, a particular configuration i (i=1, 2, ..., n) which can be used with that prevailing weather/wind combination, will be actually used only if all higher-ranked configurations, i.e. configurations 1 through i-1, cannot be used for the prevailing weather/wind combination.

The definitions of "availability" and "marginal availability" of runway configurations become important at this point. The availability of a runway configuration for each weather (i.e. ceiling and visibility) category is the percentage of time that the configuration can be used due to crosswind/tailwind constraints when the specified weather category prevails. Runway configuration availability can be determined directly from the appropriate wind/weather rose for an annual or seasonal planning period. (See next section for examples.)

The marginal availability of a runway configuration for each weather category is the percentage of time when this configuration is available while no other configuration of higher capacity is available. Marginal availabilities are also determined from the appropriate wind/weather roses (see next section for examples).

Because of the fact that computing the availability and marginal availability of runway configurations is a tedious and very time-consuming task - and becomes particularly so when a large number of runway configurations exists at an airport - work has been undertaken under this research project to develop a computer program that "automates" this task.

Step 5 of the procedure which we outlined in the previous sub-section then consists of the following steps:

(i) Rank by capacity from highest to lowest and list all configurations available for a given weather category (e.g. VFR-1, VFR-2/IFR-1, etc.)

(ii) Determine, using the appropriate wind/weather rose, the marginal availability of each configuration.

(iii) Plot the capacity of a configuration against the percentage of time corresponding to that configuration's marginal availability, as illustrated below, beginning with the highest-ranked configuration and proceeding down the ranked list of configurations. This plot is the CCC.

The following example should clarify the process. Consider the hypothetical data on Figure 3.1. For the VFR-1 weather category, four different runway configurations (A,B,C, and D) are available. A offers the highest capacity (95 operations per hour) and D the smallest (74 per hour). The data include both the total availability and the marginal availability of each configuration (obtainable from the VFR-1 weather/wind rose for that airport). For instance, Configuration B is available 39 percent of the time when VFR-1 conditions prevail at this airport, but its marginal availability is only 21 percent; for the remaining 18 percent of the time when Configuration B is available, Configuration A is also available and will be preferred to B since it offers higher capacity.

The capacity coverage chart for this set of data is shown in the lower part of Figure 3.1. Configuration C does not appear at all on the capacity coverage chart, despite its higher capacity compared to Configuration D, which does appear in the chart. The reason, as the marginal availability column indicates, is that the availability of Configuration C always coincides with the availability of a higher capacity configuration (i.e., A or B or both). Note also that for three percent of the time when VFR-1 weather prevails, the capacity of the airport in question is equal to zero. (Presumably, for three percent of the time, the wind speed and direction is such that none of the hypothetical airport's configurations is available for use).

A final comment pertains to the assumption that when two or more configurations are available, the higher capacity configuration will be used. This assumption presumes that noise preferential selection of runways is given secondary consideration when traffic demand is high; however, it does not preclude the use of noise preferential runway configurations at times of the day (or seasons of the year) when traffic demand does not approach or exceed the capacity of these configurations.

Different patterns of configuration use (as distinct from availability) would result by adopting a policy of selecting the lowest noise configuration available (provided hourly average delay did not exceed some stated value). Since this study is concerned strictly with the capacity of DEN and BOS (i.e., the maximum capability of the airport to serve aircraft demand), the derivation and use of the capacity coverage charts based on availability is entirely appropriate.

The CCC can be produced for each weather category, and/or for all categories combined. An average hourly capacity then can easily be computed for the airport for the annual or seasonal planning period. (Note that the weather/wind rose data can also be restricted to certain hours of the day corresponding to day/night, or non-curfew hours for the airport). The major advantage of using CCC is to determine exactly the improvement in capacity which would occur with introduction of new procedures, separations, or runway configurations at this airport. For example, any improvement for configuration C in Figure 3.1 will not change the CCC until it exceeds the capacity of configuration B. There are many improvements which will not affect the CCC, and vice versa. The CCC identifies those configurations and improvements which do make a contribution to increasing the overall capacity at the airport.

3.3. Application: Denver

The capacity analysis of Denver's Stapleton International Airport relied on: a FAA Delay Task Force study of the airport which was completed in 1980; weather and wind data supplied on computer tape by the National Climatic Data Center; an on-site, one-day visit with FAA terminal area personnel; and a review of extensive recent (1984) data based on tower and TRACON logs.

We now comment briefly on the application to DEN of each of the five steps of the approach described in the previous section. An airport diagram is shown in Figure 3.2.

3.3.1 Description of Steps in Computing Capacity Coverage Chart for Denver

Step 1: Weather categories, their definitions and their percentage occurrence are shown and plotted in Figure 3.3. Figures A.3.1 and A.3.2 in the Appendix to Part 3 present the information, drawn from 29,215 observations made in the 1965-74 period, on which the wind/weather roses to be used in Step 5 were based. It was learned that since the spring of 1982, DEN has been operating with a "20-knot crosswind, 10-knot tailwind" tolerance rule. Prior to that, including the period of the FAA Delay Task Force Study, a "15-knot crosswind, 7-knot tailwind" rule was in effect. This change allows more extensive use of the higher capacity configurations, increasing the airport's capacity as shown by an improved CCC.

Steps 2 and 3: The runway configurations in use at Denver are shown in Figure 3.4 together with the associated weather categories. The designation "VFR" includes both the VFR-1 and VFR-2 categories (see Figure 3.3) and "IFR" includes both IFR categories. The configurations have been numbered 1 to 11 for convenience. Comparisons of tower logs for 1984 with the FAA Delay Task Force Study of 1980, indicated that the 11 configurations shown in Figure 3.4 comprise an exhaustive list of DEN configurations and that this list was the same in 1980 and in 1984-85. At other major airports, there may be several times this number of operating configurations available.

In addition to aircraft-to-runways and operations-to-runways assignment patterns, the traffic mix has remained essentially the same since 1980 at DEN as shown by Figure A.3.3 in the Appendix to Part 3. (While the percentage of commuter/air taxi operations has increased and that of general aviation operations has decreased, the breakdown between air carrier operations, on the one hand, and commuter/air taxi plus general aviation, on the other, has remained virtually unchanged since 1980.)

Step 4: The airport capacities for each of the configurations 1-11 were obtained from the FAA Delay Task Force study and listed in Figure 3.5. Since the traffic mix and aircraft-to-runway and operations-to-runway assignment patterns have remained unchanged since 1980, as just noted, these airport capacity estimates are still valid as well. (An independent confirmation of these capacity estimates was not possible, since a model capable of representing the simultaneous operation of five active runways, as required for DEN, is not currently available at MIT).

With respect to the capacities shown in Figure 3.5, it should be noted that VFR-2 weather represents only a very small proportion of VFR weather (4.6% out of 94.6% total as indicated in Figure 3.3). Since out of the 7 VFR configurations (1-7), only in one case (that of configuration 1) is there a significant difference (about 10%) between the VFR-1 and the VFR-2 capacities time under VFR-2 conditions, it was decided to merge the VFR-1 and VFR-2 capacities into a single column, shown as simply VFR in Figure 3.5. The capacity shown in each row of the VFR column is a weighted (for percentage of use) average of the VFR-1 and VFR-2 capacities and, as might be expected,

C2

virtually the same as the VFR-1 capacity. In a similar spirit, due to the fact that IFR-1 and IFR-2 capacities are virtually identical for each of the configurations 8-11, a single IFR capacity has been used in every one of these four cases, as shown. This single capacity is again computed as the weighted average of the IFR-1 and IFR-2 capacities.

Step 5: This step involves the ranking of the 11 Denver configurations, the computation of marginal availabilities for each configuration and the plotting of CCCs for Denver. The computation of marginal availabilities for VFR weather is shown on the wind roses in Figure A.3.4 through A.3.10 of the Appendix to Part 3, while the corresponding analysis for IFR weather is shown in Figures A.3.11-A.3.14.

It is worth considering a couple of these Figures in order to explain the procedure. Consider Figure A.3.4 which refers to configuration 1, the highest ranked configuration in terms of capacity (see Figure 3.5) with a capability of 150 operations per hour. Since Configuration 1 implies use of the runway pairs 26 (and of their third parallel runway 25) and 35, the cross-hatched area in Figure A.3.4 shows the part of the wind rose "covered" by Configuration 1 for a 20-knot crosswind and 10-knot tailwind tolerance. In other words, for the annual percentage of time covered by the cross-hatched area, Configuration 1 is available for use.

Turning now to Figure A.3.5, we see that it uses the next-highest-ranked configuration, i.e. Configuration 5 with a capacity of 127 operations/hour. Configuration 5 involves the use of the pairs of runways 8 and 35. The shaded area in Figure A.3.5 represents the time already covered by Configuration 1 (this area is, of course, identical to the cross-hatched area in Figure A.3.4) while the new cross-hatched area shows the marginal availability of Configuration 5. In other words, the cross-hatched area in Figure A.3.5 shows the percentage of time when Configuration 5 is the available configuration with the highest capacity. The remaining Figures (A.3.6 through A.3.14) should now be self-explanatory.

At the completion of this procedure, i.e. after one goes through the entire list of the 11 configurations, the capacity coverage chart for DEN can be plotted. Figure 3.6 shows the CCC for IFR periods only, while Figure 3.7 shows the CCC for both IFR and VFR weather conditions at DEN.

3.3.2 Observations on Current Denver Capacity Coverage

It should be noted that DEN can operate for up to 88% of the year with configuration 1 which has a capacity of 150 operations per hour (see Figure 3.7) and for another 6% of the time with configurations whose capacities exceed 125 operations per hour. Thus for about 94% of the year the VFR capacity of DEN is already very high and is adequate for its current demand levels.

On the other hand for about 5% of the time, corresponding to IFR-1 and IFR-2 conditions, DEN's capacity is reduced to only about 60 operations per hour or barely 40% of its peak capacity. It is safe to guess that most of the major delays at DEN occur during that 5% of the time.

It turns out that the single common characteristic of the IFR configurations at DEN is that the airport operates with a single arrival stream under such conditions. Thus there seems little doubt that the single most beneficial improvement to the airport at this time would be one that provides a simultaneous IFR approach capability at DEN. This, of course, can be achieved either through the construction of a new runway (preferably in the east-west direction as suggested by Figure 3.6, which indicates the extensive use of Configurations 8 and 11 in IFR conditions, both of which require east-west landings) or through the development of advanced air navigation capabilities and procedures which allow close parallel approaches in IFR conditions. (It has recently come to our attention that the just-completed ATA Airline Industry Survey of Airports has arrived at the same conclusion.)

Finally, a comment must be made about the information on Figure 3.8, which shows the actual percentage-use of runway configurations as listed in the Delay Task Force Study in 1980. Actual percentage use can differ (and in

Denver's case does differ) from potential use due to a number of reasons, most often "noise-management"/"noise-distribution" programs. The CCC shows potential use, under the assumption that the airport will employ the highest-capacity configuration available to it at any given time.

It should, however, also be noted that, at the time of the Delay Task Force Study, Denver was operating with a "15-knot crosswind, 7-knot tailwind" rule. The change to a "20-knot crosswind, 10-knot tailwind" rule in 1982 has led to an increase in the actual use of Configuration 1 since then as examination of the 1984 log shows. In other words, while the Delay Task Force found that, up to 1980, configuration 1 was being used about 52% of the time it is clear that, following adoption of the "20-10" rule, Configuration 1 has been used more often since 1982, although it is difficult from the way the information is tabulated in the 1984 data to quantify this more precisely. The CCC analysis shows that it can be used on average for 88% of the year. Note that significant improvements in capacity can be achieved by improving crosswind and downwind landing performance at some airports.

3.4 Application: Boston

A capacity analysis similar to that for Denver was carried out at Boston's Logan International Airport. No FAA Delay Task Force study of this airport has been carried out but a 1978 study by the FAA's Office of Systems Engineering and Management was available to the project team. In addition to the FAA/OSEM study, access was available to weather and wind data on computer tapes, extensive tower-logs, and PMS (Performance Measurement System) data, as well as personal access to FAA ATC personnel at Logan.

We now outline our five-step approach as it applies to BOS. The discussion will follow a line analogous to that for DEN. An airport diagram is shown in Figure 3.9.

3.4.1 Description of Steps in Computing Capacity Coverage Chart for Boston

Step 1: Weather categories, their definitions and their percentage occurrences are shown in Figures 3.10 and 3.11. Note that the definitions of weather categories (Figure 3.10) are somewhat different from those for DEN. Logan airport is closed in IFR-4 conditions, and this case is not considered further. It is also noteworthy that the occurrence of the various weather categories does not change greatly from season to season (Figure 3.11). Wind roses for each weather category (VFR-1, VFR-2/IFR-1, IFR2, IFR-3) are shown in Figures A.3.15 through A.3.18. The reason that VFR-2 and IFR-1 are merged into a single category is because they are treated as one at BOS for purposes of runway configuration selection, ATC procedures, and separation requirements.

Steps 2 and 3: The principal runway configurations in use at BOS under normal operating conditions are shown in Figures 3.12. An associated explanatory key is given in Figure 3.13. Note that the configurations have been numbered as 1 to 17 for convenience and that the weather category under which each configuration is used is also shown next to the configuration. The 17 configurations are the same as those identified in the FAA/OSEM study of 1978.

Figure 3.12 also shows the aircraft-to-runways and operations-to-runways assignment patterns. The aircraft categories in use are defined in Figure 3.14 and the aircraft mix assumed for each weather category is shown in Figure 3.15. It is important to note that the mix is assumed to be weather-dependent. The mix shown in Figure 3.15 is based on analysis of PMS data from FAA tower records at Boston Logan from 1980. Data from 1981 and 1982 which were also available were deemed to be less representative, due first to the effects of the ATC controllers' strike (and the attendant quotas imposed on Logan), and second to the imposition of a $50 minimum daily landing fee in 1981 at Logan (which decreased the number of general aviation operations).

Step 4: MIT's RUNCAP model (actually a more-recent version of it called SUPCAP) was used to compute airport capacities under each of the 17 configurations (and associated mixes, aircraft-to-runway and operations-to-runway assignments). The results of the capacity computations are shown in Figure 3.16. Note that the capacity has been estimated for the cases in which arrivals represents 40%, 50% and 60% of hourly operations, and that at times capacity varies significantly with that percentage. We have used a 50% mix for arrivals/departures in our analysis.

Step 5: On the basis of the capacity rankings obtained in Step 4 and using the appropriate wind roses (Figures A.3.15-A.3.18), the capacity coverage charts for BOS were finally plotted. These are shown in Figures 3.17-3.20 for each of the possible weather categories.

3.4.2 Observations on Current Capacity Coverage at Boston

Boston Logan airport has VFR-1 coverage only 79% of the year, and can achieve operation rates above 100 operations per hour by operating two approach streams in Configurations 1, 9, and 6 for about 65% of the year. A typical peak-hour demand is around 80 operations per hour, and is easily handled by these configurations. When crosswinds dictate landings on Runway 33L, the capacity drops to less than peak-hour demand in VFR-1.

For the remaining 35% of the year under VFR-2/IFR-1, IFR-2, and IFR-3 weather conditions, operational capacity is well below peak-hour demands [except for Configuration 10 in VFR-2 (IFR-1)].

The need to operate a second approach system in marginal weather conditions is similar to the situation at Denver. The alternatives are to build a second runway, or to operate close parallel runways, perhaps extending 15L/33R to provide close parallel runways in that direction for VMC and IMC weather.

The VFR operational capacities at Boston Logan are around 110 operations per hour, substantially lower than Denver (150 operations per hour), where there are always parallel takeoff runways operating independently of the landing runways. The IFR capacities are similar, at around 60 operations per hour, but Boston Logan operates under these conditions for 35% of the year compared to 5% at Denver Stapleton. It is clear that there is more potential for runway capacity improvement through advanced-technology operations at Boston Logan, since Denver operates at a very high VFR capacity for most of the year.

3.5 Advanced Technology ATC Operations for Denver and Boston

In this section, we shall discuss in detail three particular ATC operations which would use advanced technology to increase the landing capacities at Denver and Boston. The potential benefit of these operations (if they can be successfully implemented) is evaluated in the next section. These discussions are speculative in nature, and require significant research effort to establish safe separation standards as a function of the achievable performance of advanced technologies in flight control, surveillance, and communication. In this section we begin to identify and describe the required research efforts.

There are three generic approach and landing operations identified and applied at Denver and Boston:

1. Split Approach Paths to a Single Runway
2. Split Approach Paths, Paired Landings on Close Parallel Runways.
3. Altitude Separation at Merge to Single Approach.

These will be discussed in order to outline the operational problems, to identify research needs, and to suggest initial goals for operational performance and separation standards.

3.5.1 Split Angled Approach Paths to a Single Runway

As briefly suggested in Part 1, there are substantial operational benefits to providing a pair of approach paths angled at $\pm 15^{\circ}$ to the centerline of a single runway. With such geometry, the problems of achieving minimal separation between successive approach aircraft in the merge area during the critical spacing function is avoided. The loss of approach capacity due to applying wake vortex longitudinal separations beyond the outer marker during merge operations is eliminated by using lateral separations. It is then possible to create a dual approach path, or "split" approach procedure which is only required to meet longitudinal time separations applied at touchdown on the runway. These separations can be expressed much more efficiently as a time (measured in seconds between landings) rather than as a distance (measured in n. miles) by the provision of advanced computer-display technology to assist the approach controller in establishing split-approach operations. The landing capacity of a single runway is significantly improved by avoiding the current distance-based separations of 3, 4, 5, and 6 n. miles. However, there are a small number of research issues which require further description to identify the role of advanced technologies in achieving split-approach operations.

3.5.1.1 The Final Turn to Runway Centerline

It is proposed as a starting point that the approach path be angled $\pm 15^{\circ}$ to the runway centerline, and that the final turn should occur around 400 feet elevation above the runway (or roughly 8000 feet and 30 seconds from touchdown). These parameters may change as a result of subsequent research, but should be chosen as constants for application of split-approach procedures at airports around the world. This would allow standardization of flight control system performance and pilot training.

The establishment of low-altitude, small-turn operations to a short final-approach path creates a number of issues to be resolved to the satisfaction of pilots and others responsible for aviation safety:

1) Should the turn be performed automatically by advanced flight control systems, or can they be performed manually by pilots given good display information?

2) What are the visibility requirements for such operations in poor weather, day/night operations to allow pilot visual acquisition of the runway and approach lighting system, and pilot orientation for manual landing operations? Are special approach lighting systems needed? What is the value of a "Heads-Up" flight display?

3) Is there a limit for crosswinds during such operations?

4) How are the angled paths defined by new approach guidance and flight navigation systems such as MLS, INS, Loran C?

5) What deviations in terms of lateral/vertical distances from centerline at a landing window after the final turn should be established as a performance criteria for acceptance of manual/automatic systems?

To evaluate the benefits of split operations at Boston and Denver, we have presumed that all approaches would be flown automatically until after the turn is completed using a MLS to define the approach paths. Under such conditions, we are expecting the deviations from the angled path to be in the order of tens of feet even with crosswinds and gusts. Ceiling/visibility limits were chosen as 800 feet/2 n. miles with current crosswind limits. Pilots would then be in visual contact with the ground roughly 1 minute before touchdown and should just be able to see the approach lighting system. The automatic turn would be performed after visual contact, and the pilot would take over for manual landing after the turn has been completed. The capability of automatic landing is well within today's technology and lower limits for manual takeover could be prescribed as a function of advanced capabilities similar to today's prescription for Cat I, II, and III straight ILS approaches.

3.5.1.2 The Safety Criteria for Gradual Merge under IMC

Due to wake-vortex considerations, the minimum spacing between landings (which ensures that the wake vortex has dissipated) is assumed to be 90 seconds, based on data gathered in Reference 1. This has also been chosen here to allow the insertion of one takeoff between landings. If a successful wake-vortex monitor is established for the touchdown area, or if smaller wake-vortex-dissipation times can be given as a function of meteorological conditions, then it may be possible to consider much higher split approach rates for a runway devoted only to landing operations. Successive aircraft at these smaller minimum spacings would be placed on alternate right/left approaches which provides a lateral spacing which gradually diminishes to the turn point.

The longitudinal spacing between successive aircraft would be monitored along the approach path with an alert system which would declare a missed approach whenever spacing errors exceeded some value. This alert criterion is dependent on the ability of aircraft to execute a prompt missed approach procedure which consists of a climbing turn away from the runway centerline. Such capability requires good ground surveillance data on along-track and cross-track position and velocity which is not available in today's terminal area radar systems. Improved ground surveillance in terms of scan rate and addressability of beacon returns, perhaps aided by downlinking data from an onboard flight control system, would be required to achieve an alert criterion of the order of 30 seconds for the projected spacing interval at the turn. The air-ground data link might also be required to transmit the missed approach command to the aircraft in a prompt fashion.

It is not clear whether the capability for an automatic missed approach would be necessary to ensure an alert criteria around 30 seconds but might be considered desirable since it is likely to be available in any advanced flight control system capable of automatically flying the angled approach, and since it would avoid the possibility of a pilot blunder in turning the wrong way during the busy cockpit activity of the missed approach. Significant research efforts are required to provide data on the safety levels provided by an alert criterion around 30 seconds, on the creation of a more complex alert criterion which might be a function of longitudinal position on approach, and to provide evidence on the spacings achieved during execution of missed approach procedures under IMC.

Note that by selecting 800 feet altitude for visual conditions, the minimal lateral separation between approach paths under IMC is 4140 feet, which is only 160 feet less than current separation standards for independent ILS operations.

3.5.1.3 Establishing Accurate Spacing Intervals

While split approach operation provides lateral spacing between successive aircraft at the initiation of landing approaches, it also creates difficulty for the controller in providing good longitudinal spacings. There are research issues to be resolved in providing an advanced display system to assist the final spacing controller in establishing the desired longitudinal position of each aircraft. As each aircraft "arrives", decisions must be made concerning the sequence of aircraft, and assignments to left/right approach paths. Aircraft must be "metered" to smooth peaks in arrival rate (which determines the landing capacity rate), and which thereby create a "busy period" where a string of landing operations at minimum spacings is created before a gap in landings occurs.

The controllers can be provided with automated decision support systems which assist them in establishing an efficient time schedule for landing operations during a busy period. This would use a graphic display of "approach boxes" which would show the desired or scheduled position of each aircraft on its angled approach path as a function of its declared approach airspeed and knowledge of current wind effects on approach groundspeeds. (If 4-D flight control systems are available, an approach groundspeed could be declared). The controller's spacing task is thus reduced to vectoring all aircraft from their current positions to intercept their assigned boxes as they move along the extended approach path. This task can be performed automatically with a computer generated set of 4-D conflict-free terminal area paths, or can be accomplished by controllers with interactive cues from the computer decision support system. By graphically manipulating the boxes, controllers could revise the computer schedule, changing landing times, landing sequence, and path assignment if deviation from an optimal, earliest completion time schedule is desired. The accuracy of landing intervals at the runway is determined by the accuracy of achieving interception with its assigned box and in maintaining longitudinal conformance with the box by commanding small speed changes. Aircraft with 4-D flight control systems could maintain longitudinal conformance automatically without controller intervention, if the desired position/times were transmitted to the aircraft via datalink.

The creation of such an automated decision support system for assisting the controllers in operating an efficient landing operation has not been accomplished, although there have been several research efforts towards similar goals over the past twenty years. Current technology in artificial intelligence, operations research, and interactive computer displays provides an improved environment for achieving successful results from future research efforts. Split approach operations would require an operational system which establishes an efficient landing schedule for aircraft with various desired approach speeds, and which is able to operate at capacity rates by providing automated assistance in achieving accurate spacings.

3.5.2 Split Approach Paths to Close Parallel Runways

In VMC conditions, controllers effectively double the IMC landing rate of dependent, close parallel runways by conducting paired or simultaneous landings. Each pair of landings is spaced longitudinally from the prior pair, as required by wake vortex separations. The wake vortices of a pair of simultaneous-landing aircraft cannot affect the other aircraft. Split approach operations with a landing schedule are capable of extending paired simultaneous landings, on close parallel runways to lower visibility/ceilings if altitude separation is used to merge slower aircraft onto each approach path. This operation will be described in the next subsection. Here we describe the operational issues associated with extending paired operations to close parallel runways.

With automated asistance in scheduling and spacing, aircraft would be conforming to their scheduled approach boxes as they approach the visual contact points at 800 feet altitude, 16,000 feet from touchdown with a nominal lateral separation of the parallel runways plus 4140 feet (eg. if runways were spaced at 1500 feet, the nominal lateral separation at visual breakout would be 5640 feet). Visibility of 1 n. mile would be required to establish visual contact with any other aircraft exactly opposite on a simultaneous breakout. The limits of 2 n. miles were selected for angled split approaches to allow runway orientation before the turn, and would allow visual contact with any slower approach speed aircraft on the opposite parallel runway which would be between the runway and the faster aircraft. (They would be landing simultaneously at the runways.) Thus, the cockpit crew of the faster aircraft would have roughly 30 seconds to establish visual contact and orientation with the runway, and visual contact with the other aircraft before the aircraft performs the turn to final approach automatically.

At night, or in poor visibility conditions, it would be desirable to color-code the centerlines of the approach lighting systems for each parallel runway, and perhaps provide similarly-colored angled entry lights. Other colored lights could be used to establish a "fence" or "no transgression zone" between the runways. Flight simulation research studies would be required to establish the value of various geometries of these approach lighting systems.

3.5.3 Altitude Separation at Merge to Single Approach Path

When the angled approach paths are used to operate landings on close parallel runways, the problem of maintaining separation during the merge phase re-occurs. There is a second method of providing approach spacings based solely on wake-vortex-dissipation times which can be effective, assuming the range of approach speeds is limited.

It applies vertical separation between successive aircraft during approach operations and requires automatic coupling to initial approach altitudes and glide slopes. Slower aircraft are assigned to an initial approach altitude 500 feet higher than faster aircraft and initiate their glide path roughly 10,000 feet further away from the runway. Since these operations are at low altitude, this proposes that safe IFR altitude separation between aircraft with altitude autocoupling and confirmed altimeter settings during merge spacing operations can be established as 500 feet. This separation is currently used between VFR and IFR aircraft at these low altitudes.

Since the higher aircraft is slower, the 10,000 feet of longitudinal separation will increase to greater distance and time separations at the runway, which will reduce landing capacity unless the speed ranges for traffic on approach are limited. The critical time separation now occurs at the glide slope initiation point of the faster aircraft where it will be lower than that achieved at the runway. At this point, the wake vortex will be below the nominal vertical path so that vertical as well as longitudinal separation from the vortex can be achieved if both aircraft conform closely to the nominal path. This would allow reduced longitudinal separations at the glide-slope initiation path. If the next aircraft after the "slow" aircraft is faster, it will achieve minimal time separation at the runway and will not require vertical separation during merge. If the next aircraft is also slower, a loss in landing capacity may be incurred as the wake vortex time separation may have to be applied at the merge point, unless another 500-foot-higher approach can be executed. To minimize these losses, the faster aircraft should be segregated onto one of the split approach paths. If the range of approach speeds can be limited to ±10 knots by this means, the additional time separation at merge (or increase in landing intervals) is of the order of 10 seconds for normal approach speeds and outer marker distances.

A key issue in maintaining vertical separation from the wake vortex is the conformance of the faster aircraft to the nominal vertical path at its glide path initiation. The slower aircraft will be already established on the glide path as it passes the point where the faster aircraft began its glide path. The automatic system for coupling to the glide path should be designed to initiate the descent without over-shooting the glide path. Good information on distance to the runway and groundspeed are required to ensure a smooth interception of the glide path from below for all aircraft. With good conformance of the automatic flight control systems at the glide path initiation point, it becomes possible to consider reduction in wake vortex time spacings over that required at the runway where no vertical separation can be assured.

3.6 Evaluation of Capacity Benefits from Advanced Technology Operations at Denver and Boston

In this section, we will introduce some of the advanced-technology operations discussed in the previous sections to current runway configurations at Denver and Boston, in order to evaluate their potential impact on the CCC and overall airport capacity. We shall briefly describe the advanced-technology ATC operation for each configuration and indicate its new capacity. To simplify the presentation, we are restricting the mix of operations to 50% arrivals/50% departures. In many cases, there is excess departure capacity available.

3.6.1 Advanced-Technology Operations at Denver

The Denver configurations are always some combination of close parallel runways for either (or both) arrival and departure operations. If we assume 90- and 120-second spacings for landings behind Heavy and non-Heavy aircraft, and add a 5-second buffer for spacing and speed uncertainty, then the 8% mix of Heavy aircraft currently at Denver results in a landing capacity of 74 landings per hour for the application of Split Approach, Paired Landings to any of these configurations. Since we are restricting ourselves to a 50% departure mix, the operational capacity is estimated at 148 per hour.

This value is actually slightly less than the 150 operations per hour estimated by the 1980 Task Force Delay Study for Configuration 1, which is available 88% of the year. Thus, there cannot be any substantial improvement expected for Denver, unless the spacings of 90 and 120 seconds chosen here for wake-vortex safety are reduced. However, this capacity of 148 operations per hour also applies to all other VFR configurations at Denver, which were estimated at capacities of 127 and less for the remaining 6.5% of VFR during the year.

This capacity also applies to IFR-1 operations at Denver for all available configurations, which provides an additional 1.4% coverage. In IFR-2 (less than 800-foot ceiling and 2 n. miles), operations are limited to a single runway. If split approach operations using 90- and 120-second intervals are used, the landing capacity is 37 landings per hour, for an operational capacity of 74 per hour. With split-approach, timed-landing operations, this can be accomplished using one runway, although there is always a pair of additional takeoff runways available, so that the 50% departure restriction may be causing an understatement of the improvement over the 60 operations per hour estimated by the Task Force Delay Study.

The improvement in the Denver CCC is shown in Figure 3.21 by the shaded areas. The current overall yearly average capacity at Denver as estimated by the Task Force is 143.8 operations per hour. With the application of advanced-technology split-approach operations, this value is increased to 150.1 operations per hour -- a small increase of only 4.7% since there are currently high-capacity VFR operations available at Denver for almost 90% of the year. (It is not clear that the Task Force capacities were restricted to a 50% departure mix so that there may be a larger increase in landing capacity than 4.7%). In VFR conditions, the overall average capacity at Denver is 148 operations/hour for both current and advanced-technology operations. The improvement comes in IFR operations where the current annual average is 60.8 operations per hour, which increases to 74 operations per hour with advanced operations.

As stated earlier, the single most-beneficial improvement to Denver would be one that provides two simultaneous IFR-2 approaches. This would require another runway to be constructed, unless automatic evasive missed-approach procedures can be implemented for simultaneous landings in the 17 and 26 directions, as recommended by the 1980 Task Force.

This evaluation of advanced-technology operations in the form of split-approach operations at Denver would indicate that there is very little benefit overall, and very little potential for any improvement over current VFR operations which apply for 95% of the year.

3.6.2 Advanced-Technology Operations at Boston

With the same assumptions of 90- and 120-second wake-vortex separations, and the 10% mix of Heavy aircraft at Logan, the highest VFR capacity change is to Configuration 9, which has two unrestricted landing runways. Its capacity with application of split approaches to Runways 22L and 27 is 146.8 operations per hour, while Configuration 1, which has close parallel landings on 04R/04L, and has noise restrictions on the use of 04L to small aircraft, then obtains an effective capacity of only 132.8 operations per hour. Notice that these restrictions segregate the slower/faster approach speeds onto 04R/04L, and ease the problems of using vertical separation at merge on each split approach. Configuration 1 would be using paired operations to achieve more-or-less simultaneous VMC touchdowns on runways spaced roughly 1600 feet apart. Configuration 6 has a similar split paired-approach operation with a restriction on the use of Runway 22R for non-jet aircraft. It achieves a capacity of 126 operations per hour. The final VFR-1 configuration shown in the CCC of Figure 3.22 is Configuration 11, with landings on 33L and landings of small aircraft on the short, close parallel runway 33R. As can be seen, there is substantial improvement in VFR-1 operations capacity at Boston Logan. The current average VFR-1 capacity is 100.7 operations per hour, whereas it is increased by 28% to 129.3 operations per hour with the split-approach operations.

Figure 3.23 shows the marked improvement in VFR-2/IFR-1 conditions at Boston Logan when split-approach operations are introduced. Under Configuration 10, there are simultaneous approaches to convergent 50^{o} Runways 22R and 27 which requires evasive turns to be included in the missed-approach paths. The current average annual capacity under these weather conditions at Boston is 71.7 operations per hour. It is increased by 64% to 117.9 operations per hour with split-approach operations. This applies for 12.1% of the year and changes the capacity from being inadequate to meet peak-hour demands currently, to a situation where there is an ample margin over demand.

The remaining improvements at Boston with advanced-technology operations are shown in Figure 3.24 and 3.25. For IFR-2 (800 feet/1 n. mile to 200 feet/0.5 n. mile), which occurs 7.8% of the year, here is an improvement of 30% from an overall capacity of 54.4 to 70.8 operations per hour for configurations which operate a single approach. For IFR-3 (below 200 feet and 0.5 n. mile) which occurs only 0.8% of the year, the increase is 23% from 56.6 to 69.8 operations per hour.

The overall annual improvement from split-approach operations at Boston Logan is a substantial 37% increase in capacity from 92.9 to 128.1 operations per hour. This is in contrast to the small 4.7% increase achieved at Denver, from much-higher values of 143.8 currently to 150.1 operations per hour with advanced technology.

APPENDIX TO PART 3:

FIGURES A.3.1 TO A.3.18

FIGURE A.3.1 WIND ROSE DATA FOR DENVER STAPLETON

A L L   W E A T H E R

DENVER, CO
STAPLETON INTL AP

ANNUAL

PERIOD OF RECORD 1965-74
29215 OBSERVATIONS

WIND DIRECTION VS WIND SPEED (PERCENT FREQUENCY OF OBSERVATIONS)

WIND	WIND SPEED (KNOTS)										
DIR	0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	OVER 40	TOTAL	AVG SPEED
N	0.6	2.9	3.2	1.6	0.3	0.1	0			8.7	8.3
NNE	0.4	1.5	1.6	0.8	0.2	0	0			4.5	8.1
NE	0.4	1.6	1.6	0.6	0.1	0				4.3	7.4
ENE	0.4	1.5	1.3	0.5	0	0				3.7	6.9
E	0.7	2.6	1.9	0.5	0	0				5.7	6.6
ESE	0.5	1.9	1.4	0.3	0	0				4.1	6.6
SE	0.5	1.8	1.3	0.4	0	0				4	6.6
SSE	0.5	1.9	1.4	0.5	0.1	0	0			4.4	7.2
S	1.2	7.2	8.9	2.5	0.3	0	0			20.1	7.6
SSW	0.7	4.6	4.4	1	0.1	0				10.8	7
SW	0.7	2.4	1.6	0.4	0.1	0				5.2	6.6
WSW	0.4	1.3	0.7	0.2	0.1	0				2.7	6.4
W	0.2	0.8	0.9	0.8	0.3	0.1	0			3.1	9.8
WNW	0.2	0.7	0.9	0.9	0.4	0.1	0			3.2	10.8
NW	0.3	1.4	1.3	0.9	0.3	0.1	0			4.3	9.2
NNW	0.3	1.5	1.4	0.7	0.1	0		0		4	8
CALM	6.5									6.5	
TOTAL	14.6	35.8	33.7	12.6	2.6	0.6	0.1	0		100	7.1

ALL WEATHER: ALL WIND OBSERVATIONS

FIGURE A.3.2 WIND ROSE DATA FOR DENVER STAPLETON

I F R

DENVER, CO
STAPLETON INTL AP

ANNUAL

PERIOD OF RECORD 1965-74
29215 OBSERVATIONS

WIND DIRECTION VS WIND SPEED (PERCENT FREQUENCY OF OBSERVATIONS)

WIND	WIND SPEED (KNOTS)									
DIR	0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	OVER 40	TOTAL	AVG SPEED
N	0.1	0.3	0.5	0.4	0.1	.0				1.4	9.5
NNE	.0	0.2	0.2	0.2	.0	.0	.0			0.6	9.1
NE	.0	0.2	0.2	0.1	.0	.0				0.5	7.7
ENE	.0	0.1	0.2	0.1						0.4	7.7
E	.0	0.1	0.1	.0						0.3	6.3
ESE	.0	0.1	.0	.0	.0					0.1	6.4
SE	.0	.0	.0	.0						.0	5.7
SSE	.0	.0	.0	.0	.0					.0	6.7
S		0.1	.0							0.1	5.5
SSW	.0	.0	.0							0.1	5.2
SW	.0	.0	.0	.0	.0					.0	4.9
WSW	.0	.0								.0	3.6
W	.0	.0	.0							.0	6.2
WNW	.0	.0	.0							0.1	6.9
NW	.0	0.1	0.1	.0	.0					0.2	7.6
NNW	.0	0.2	0.2	0.1	0.1			0		0.5	7.8
CALM	0.2									0.2	
TOTAL	0.6	1.5	1.7	0.8	0.1	.0	.0	0		4.7	7.7

IFR WEATHER: CEILING < 1000 FT AND/OR VISIBILITY < 3 MI BUT >= 200 FT AND >= 1/2 M

FIGURE A.3.3 ANNUAL AIRCRAFT OPERATIONS AT STAPLETON INTERNATIONAL AIRPORT (DEN)

FY	AIR CARRIER	%	COMMUTER/ AIR TAXI	%	GENERAL AVIATION	%	MILITARY	%	TOTAL OPERATIONS
1980	316,664	65.2	56,689	11.7	109,329	22.5	3,013	0.6	485,695
1981	315,087	65.8	60,542	12.6	101,616	21.2	1,815	0.4	479,060
1982	310,208	66.4	67,747	14.5	88,209	18.9	1,344	0.3	467,508
1983	322,275	69.0	67,049	14.4	76,225	16.3	1,287	0.3	466,836
1984	326,964	67.0	89,333	18.3	70,342	14.4	1,653	0.3	488,297

FY	AIR CARRIER & COMMUTER/AIR TAXI	%	COMMUTER/AIR TAXI & GENERAL AVIATION	%
1980	373,353	76.9	166,018	34.2
1981	375,629	78.4	162,158	33.8
1982	377,955	80.8	155,956	33.4
1983	389,324	83.4	143,274	30.7
1984	416,302	85.3	159,680	32.7

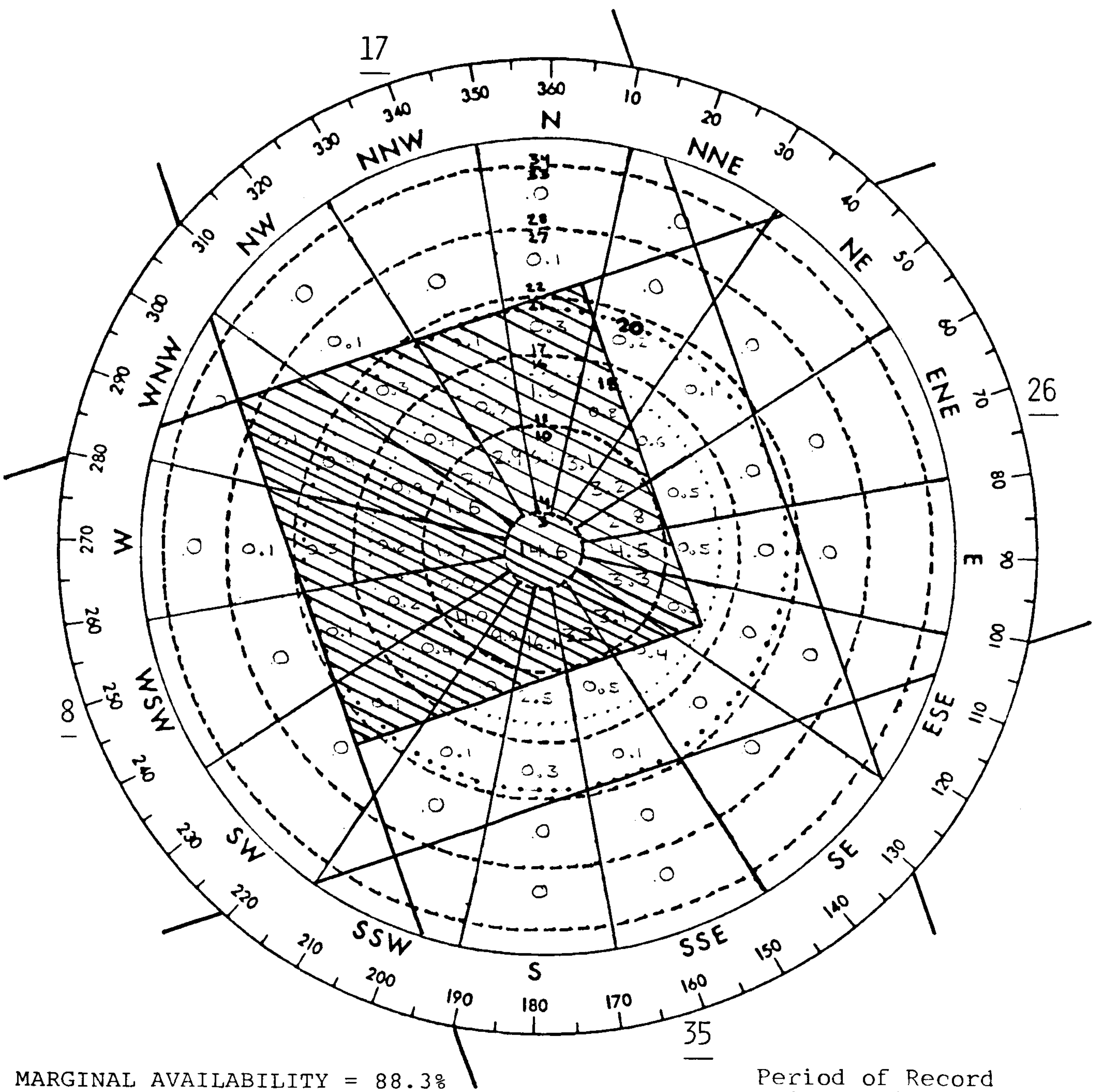
* Source: FAA Air Traffic Activity Reports

FIGURE A.3.4

- ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 1 - DENVER STAPLETON -

CAPACITY = 150 OPS/HOUR



MARGINAL AVAILABILITY = 88.3%

CUMULATIVE AVAILABILITY = 88.3%

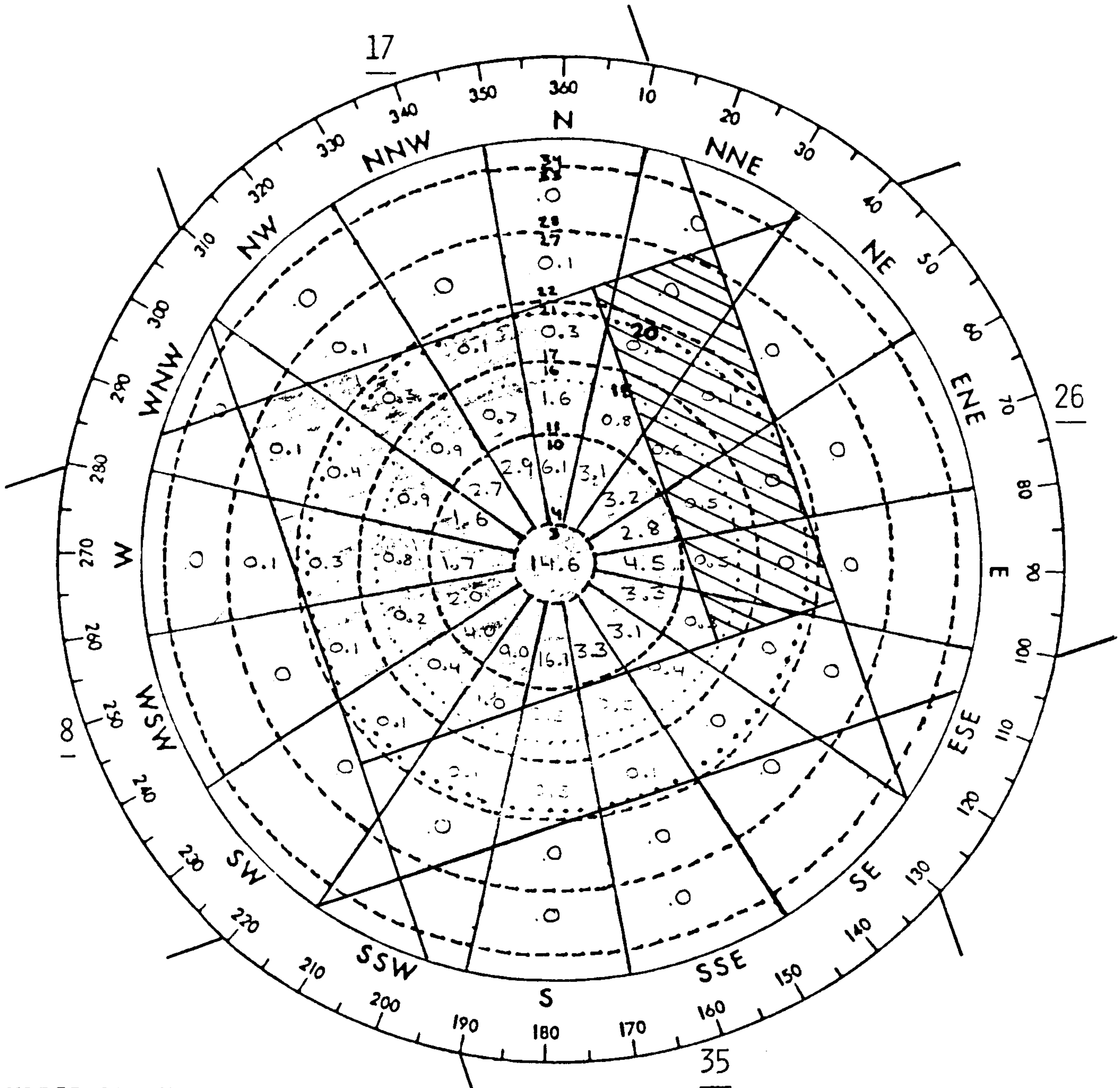
Period of Record
1965 - 1974
Annual

FIGURE A.3.5

ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 5 - DENVER STAPLETON

CAPACITY = 127 OPS/HOUR



MARGINAL AVAILABILITY = 2.62%

CUMULATIVE AVAILABILITY = 90.92%
(over configuration 1)

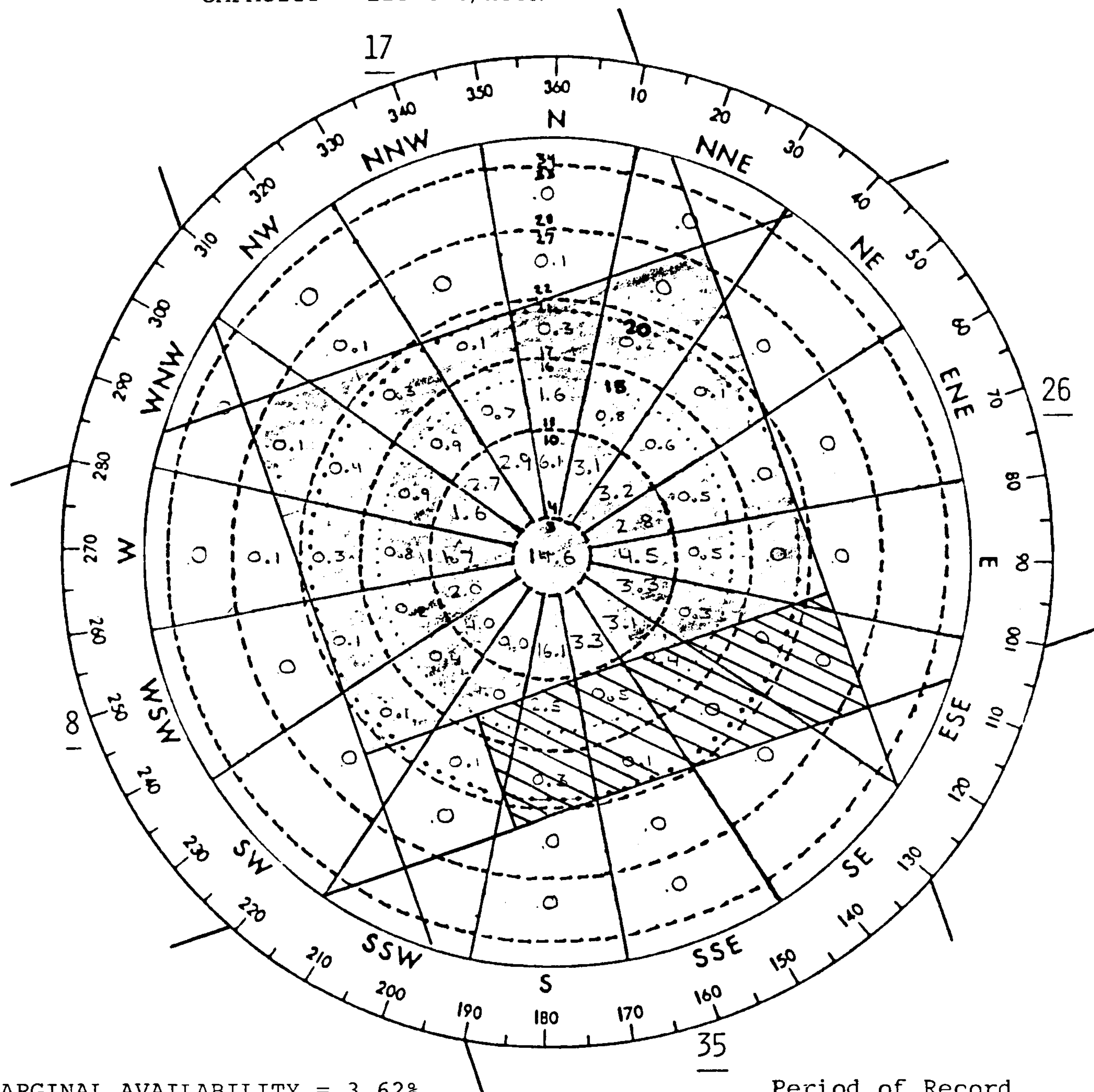
Period of Record
1965 - 1974
Annual

FIGURE A.3.6

ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 3 - DENVER STAPLETON -

CAPACITY = 125 OPS/HOUR



MARGINAL AVAILABILITY = 3.62%

CUMULATIVE AVAILABILITY = 94.54%

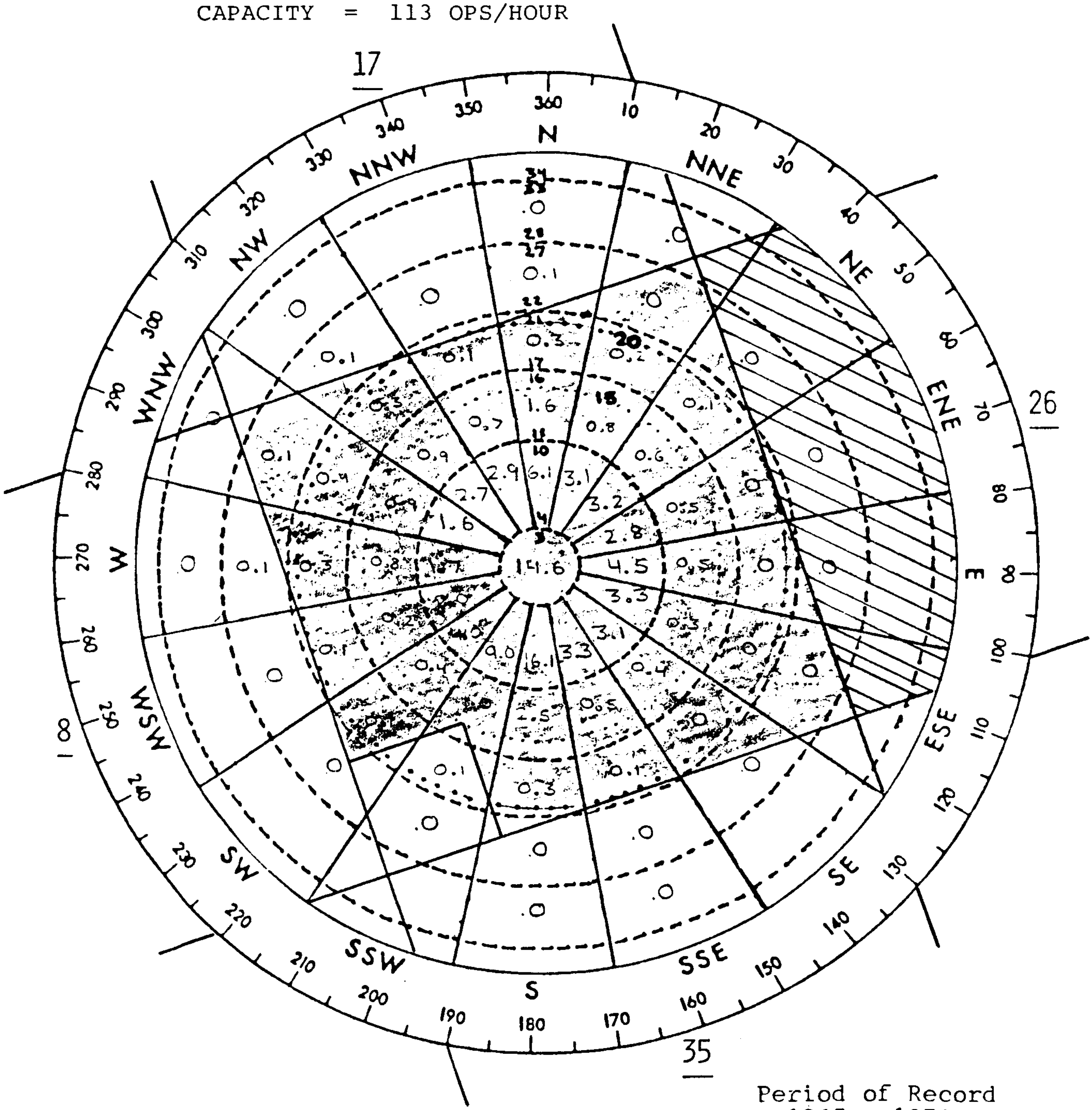
Period of Record
1965 - 1974
Annual

FIGURE A.3.7

ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 7 - DENVER STAPLETON -

CAPACITY = 113 OPS/HOUR



MARGINAL AVAILABILITY = 0.1%

CUMULATIVE AVAILABILITY = 94.64%

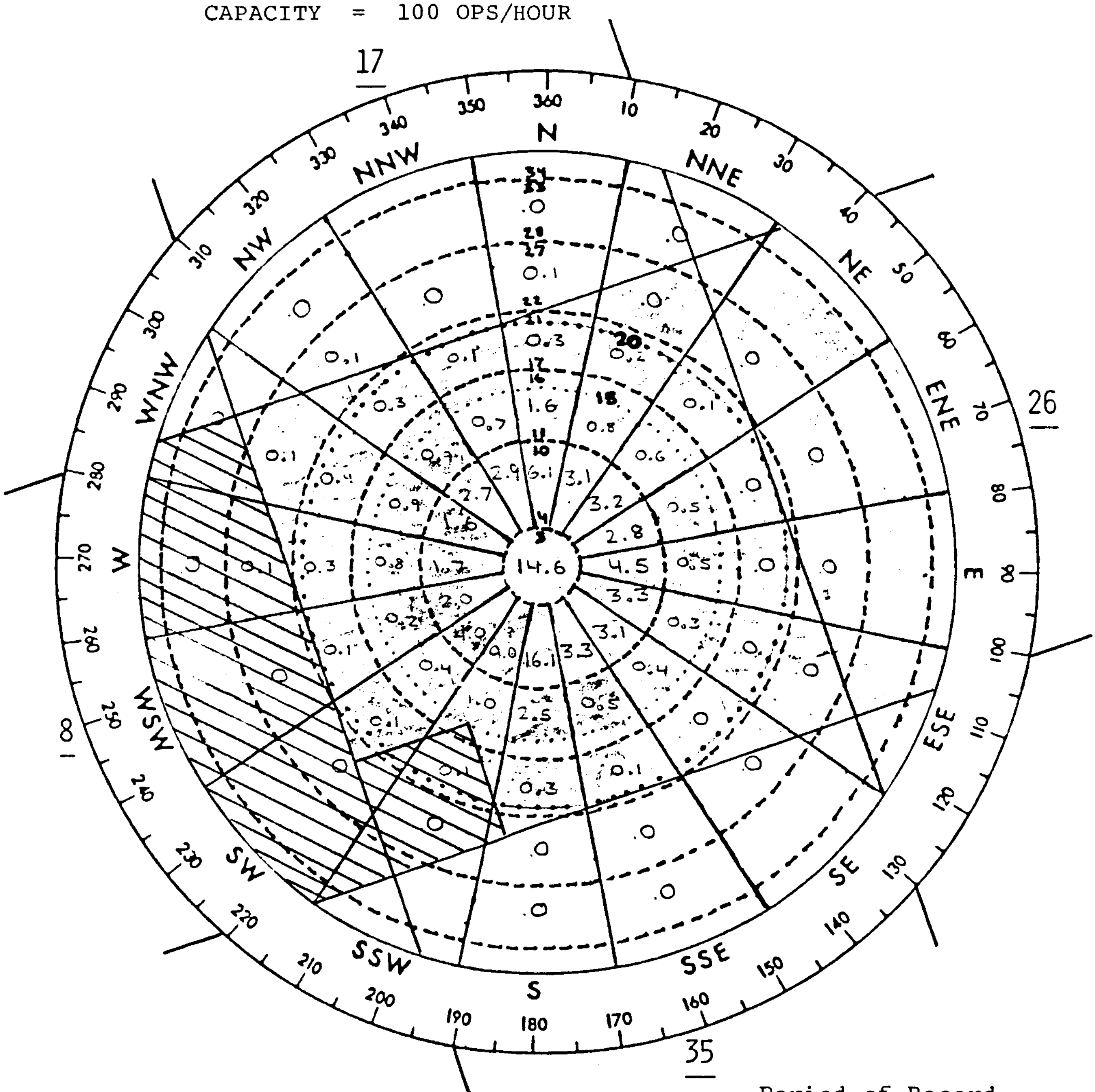
Period of Record
1965 - 1974
Annual

FIGURE A.3.8

ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 4 - DENVER STAPLETON -

CAPACITY = 100 OPS/HOUR



MARGINAL AVAILABILITY ≐ 0.22%

CUMULATIVE AVAILABILITY = 94.9%

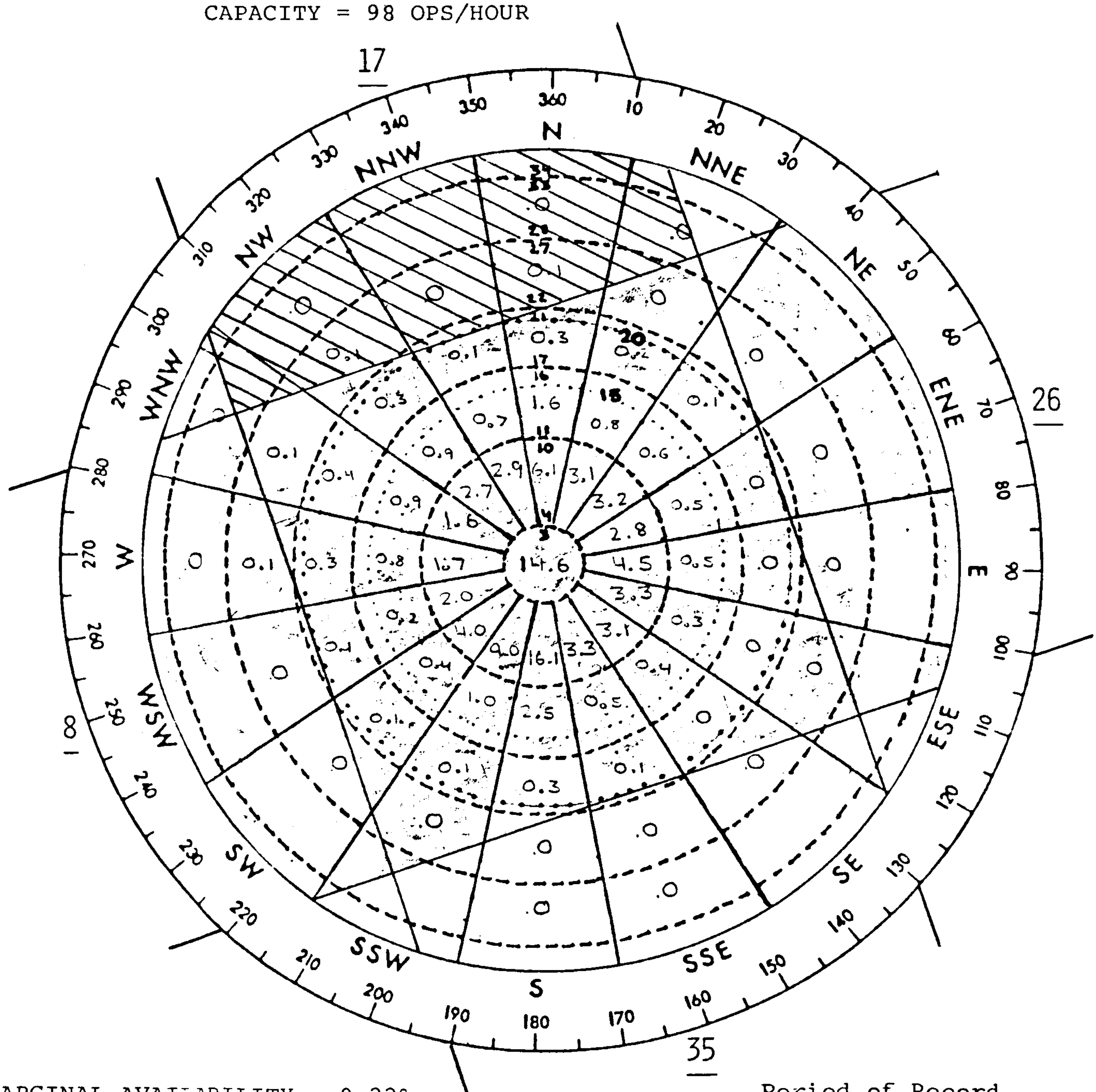
Period of Record
1965 - 1974
Annual

FIGURE A.3.9

ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 2 - DENVER STAPLETON -

CAPACITY = 98 OPS/HOUR



MARGINAL AVAILABILITY = 0.22%

CUMULATIVE AVAILABILITY = 95.08%

Period of Record
1965 - 1974
Annual

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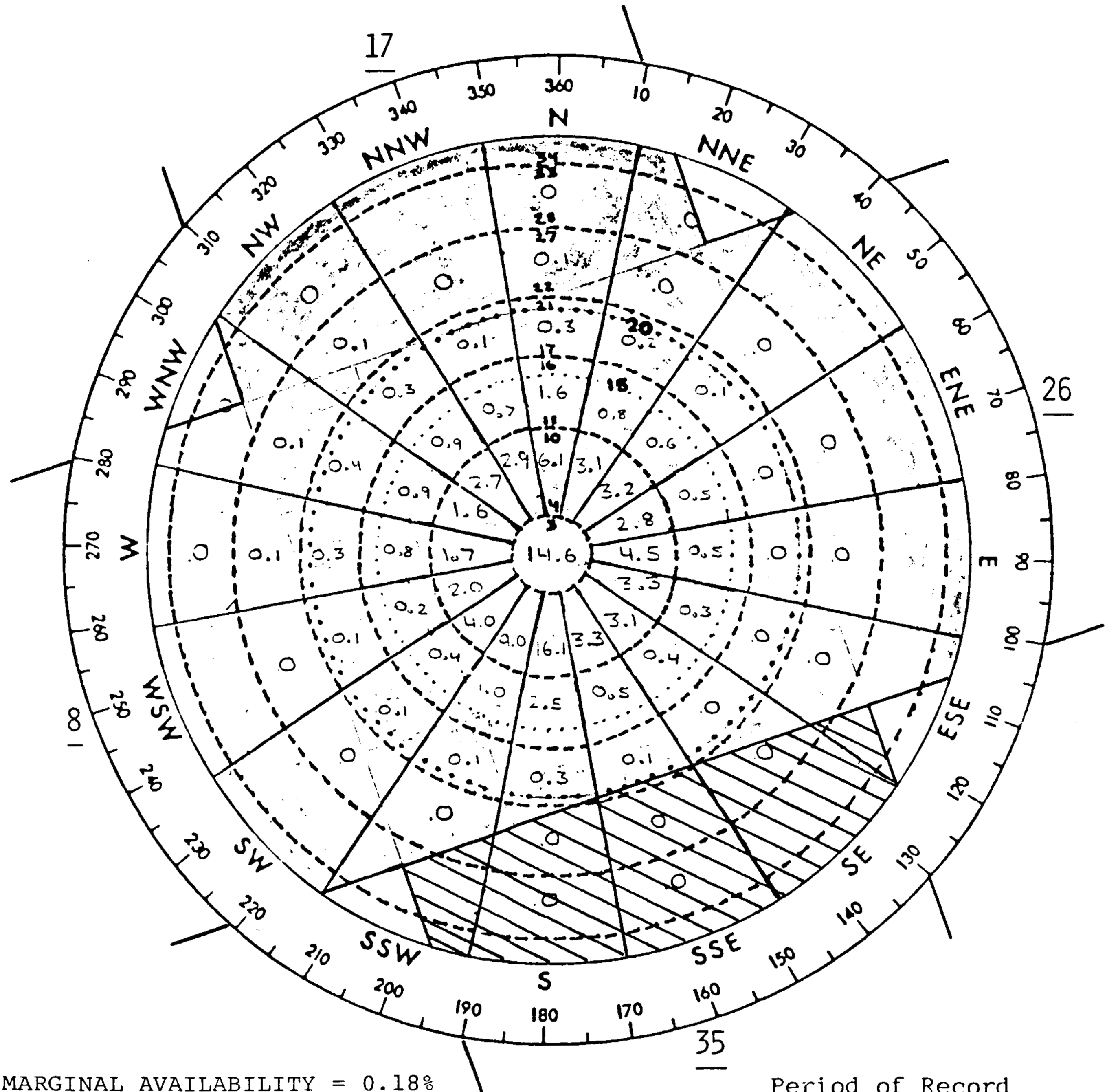
FIGURE A.3.10

ALL WEATHER WIND ROSE FOR CAPACITY ANALYSIS

VFR CONFIGURATION 6 - DENVER STAPLETON -

CAPACITY = 95 OPS/HOUR



MARGINAL AVAILABILITY = 0.18%

CUMULATIVE AVAILABILITY = 95.26%

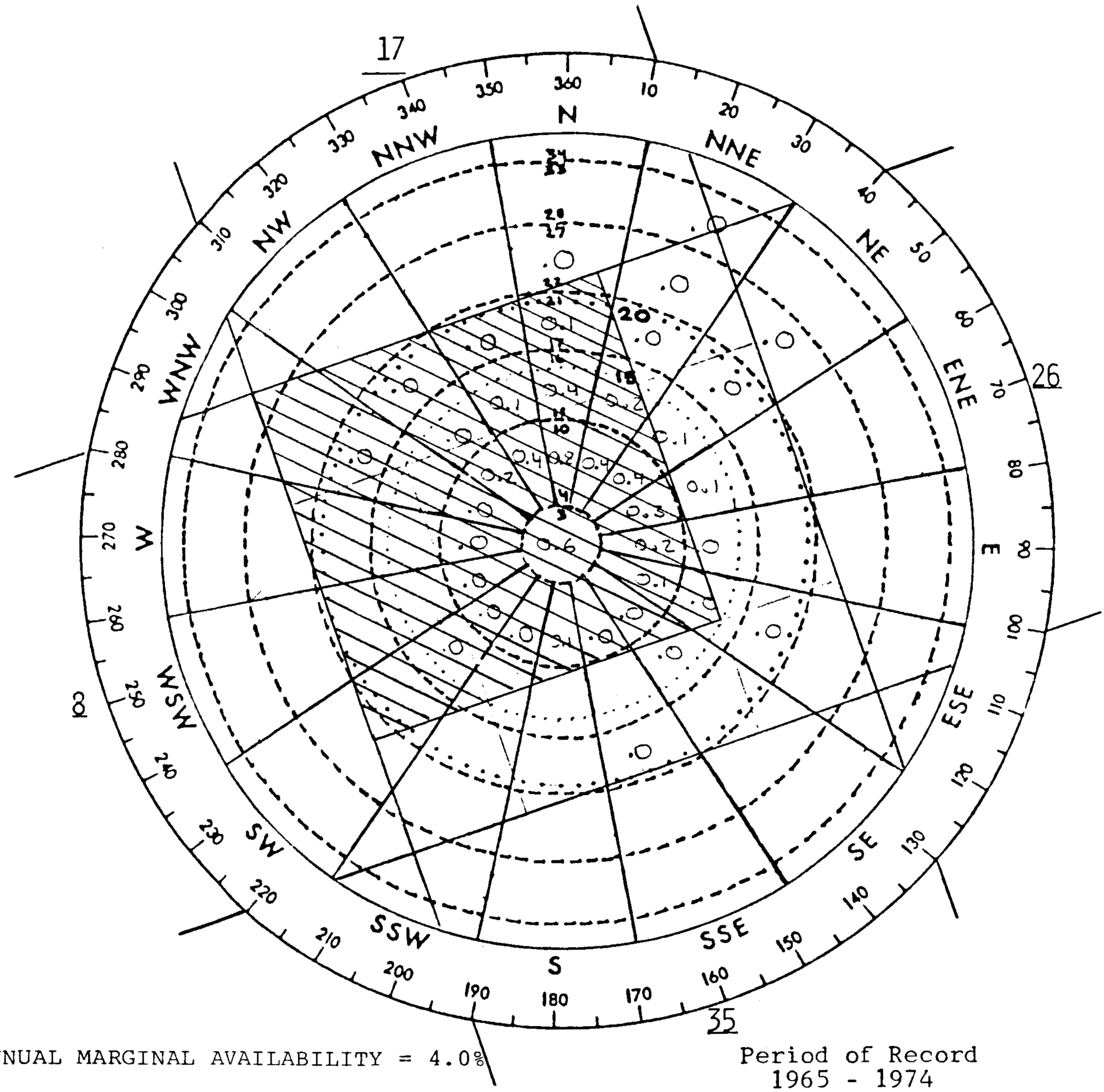
Period of Record
1965 - 1974
Annual

FIGURE A.3.11

IFR WEATHER WIND ROSE FOR CAPACITY ANALYSIS

IFR CONFIGURATION 8 -DENVER STAPLETON -

CAPACITY = 61 OPS/HOUR



ANNUAL MARGINAL AVAILABILITY = 4.0%

CUMULATIVE AVAILABILITY = 4.0%

Period of Record
1965 - 1974
Annual

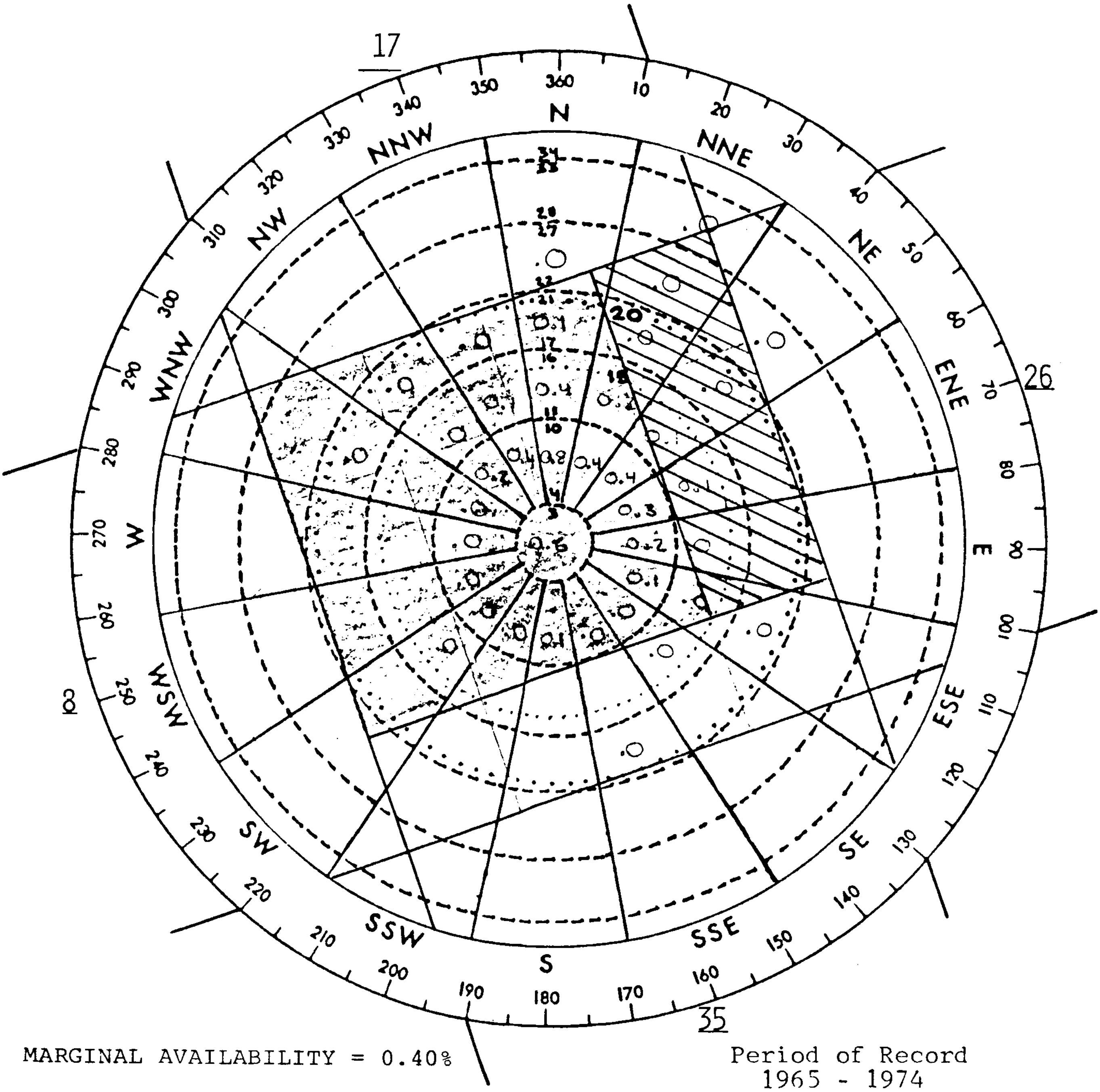
IFR: Ceiling < 1000 ft and/or Visibility < 3 mi but ≥ 200 ft and ≥ 1/2 mi

FIGURE A.3.12

IFR WEATHER WIND ROSE FOR CAPACITY ANALYSIS

IFR CONFIGURATION 11 - DENVER STAPLETON -

CAPACITY = 60 OPS/HOUR



MARGINAL AVAILABILITY = 0.40%

CUMULATIVE AVAILABILITY = 4.4%

Period of Record
1965 - 1974
Annual

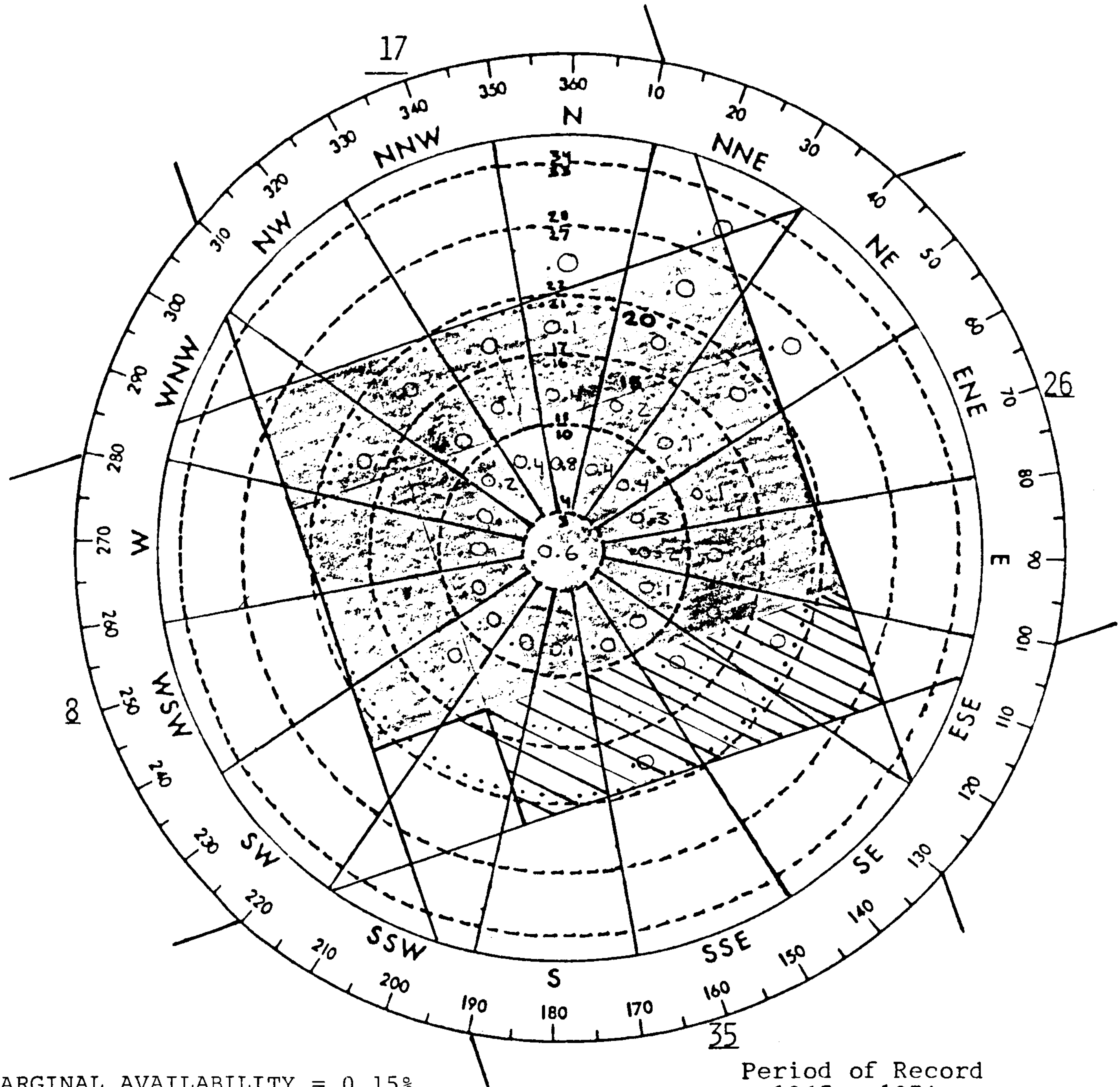
IFR: Ceiling < 1000 ft and/or Visibility < 3 mi but ≥ 200 ft and ≥ 1/2 mi

FIGURE A.3.13

IFR WEATHER WIND ROSE FOR CAPACITY ANALYSIS

IFR CONFIGURATION 10 - DENVER STAPLETON -

CAPACITY = 60 OPS/HOUR



MARGINAL AVAILABILITY = 0.15%

CUMULATIVE AVAILABILITY = 4.55%

Period of Record
1965 - 1974
Annual

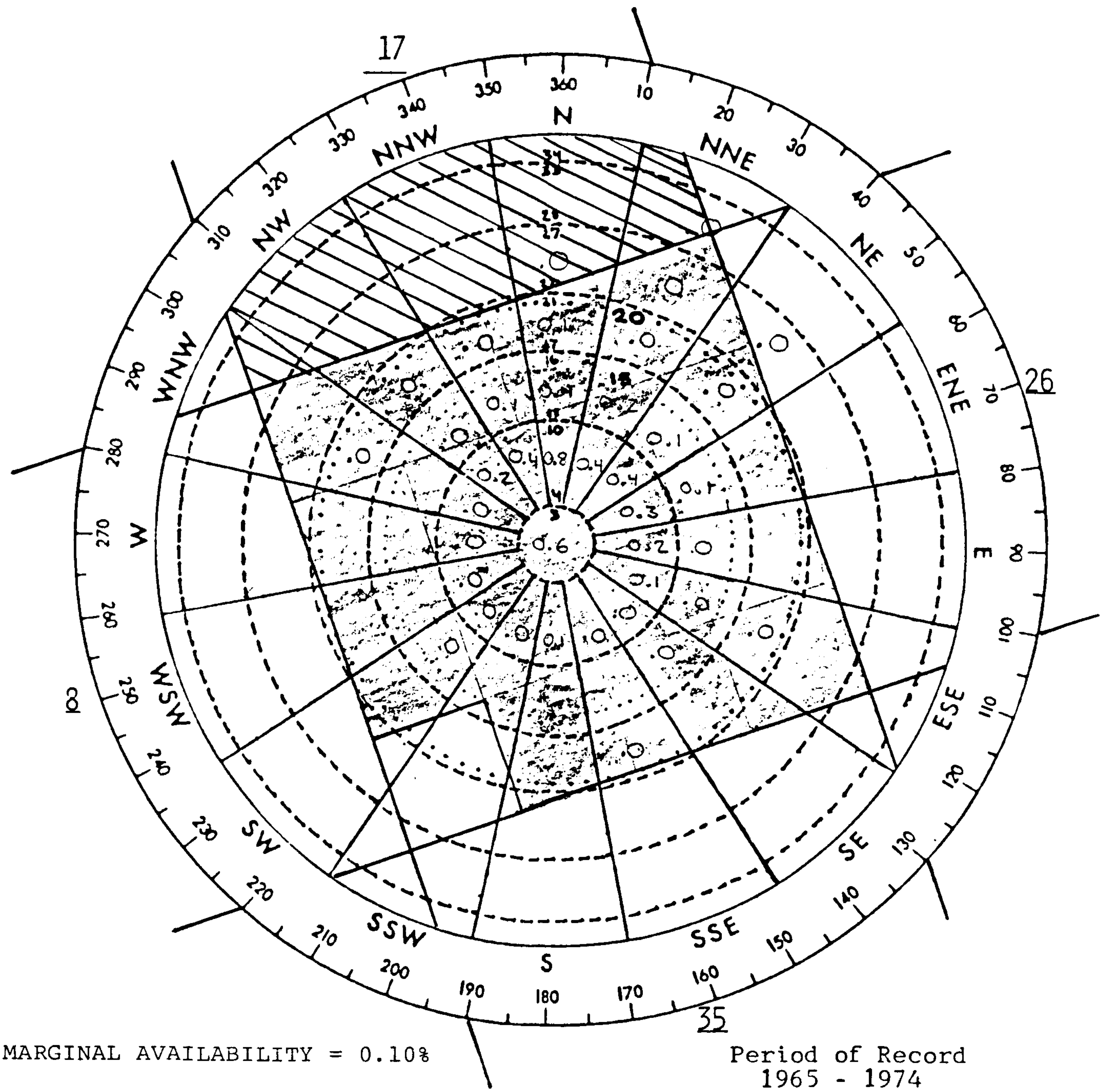
IFR: Ceiling < 1000 ft and/or Visibility < 3 mi but ≥ 200 ft and ≥ 1/2 mi

FIGURE A.3.14

IFR WEATHER WIND ROSE FOR CAPACITY ANALYSIS

IFR CONFIGURATION 9 - DENVER STAPLETON -

CAPACITY = 59 OPS/HOUR



MARGINAL AVAILABILITY = 0.10%

CUMULATIVE AVAILABILITY = 4.65%

Period of Record
1965 - 1974
Annual

IFR: Ceiling < 1000 ft and/or Visibility < 3 mi but ≥ 200 ft and ≥ 1/2 mi

Figure A 3.15

BOSTON-LOGAN WIND ROSE
1972-1978 OBSERVATIONS
0600-2300 LOCAL TIME

Weather Category: VFR-1

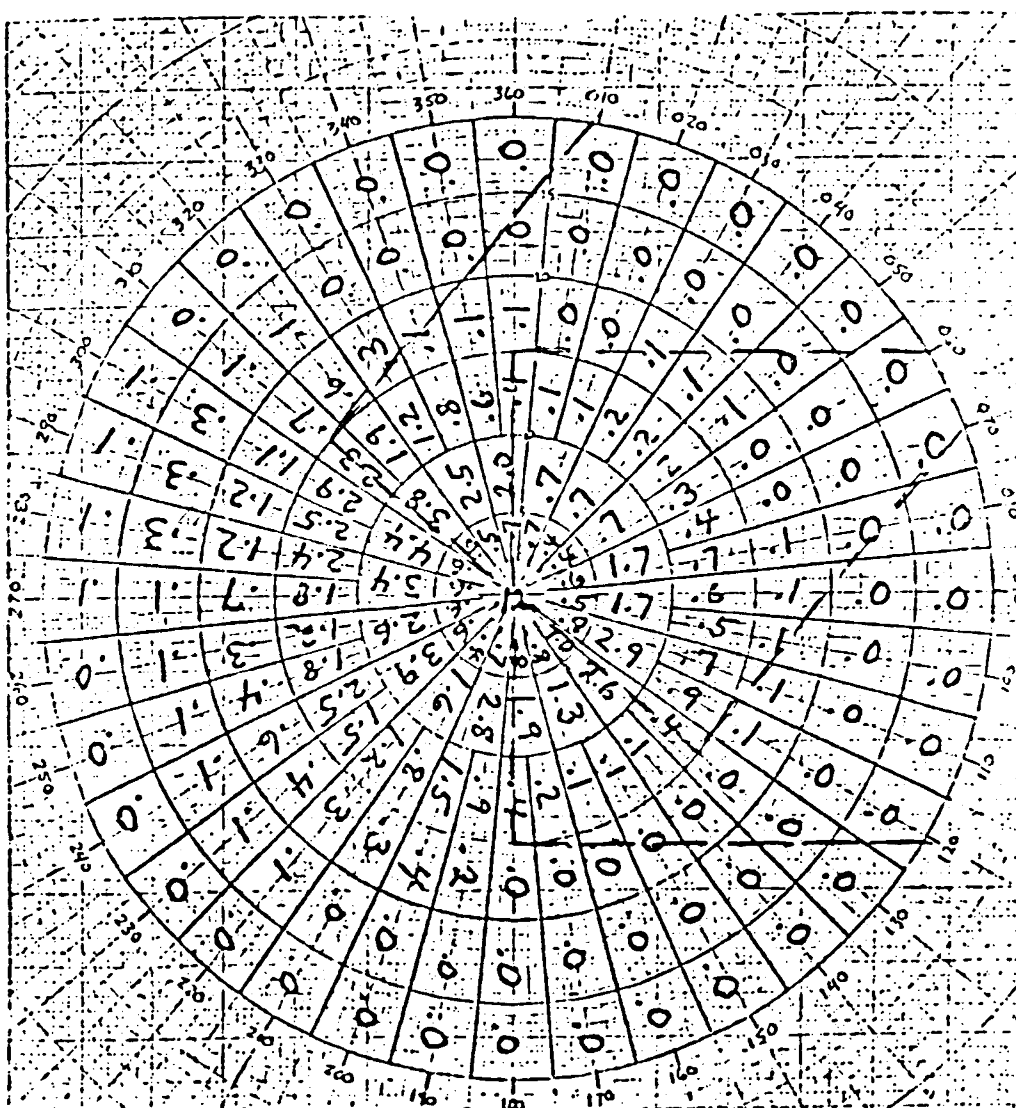


Figure A 3.16

BOSTON-LOGAN WIND ROSE
1972-1978 OBSERVATIONS
0600-2300 LOCAL TIME

Weather Category: IFR-1/VFR-2

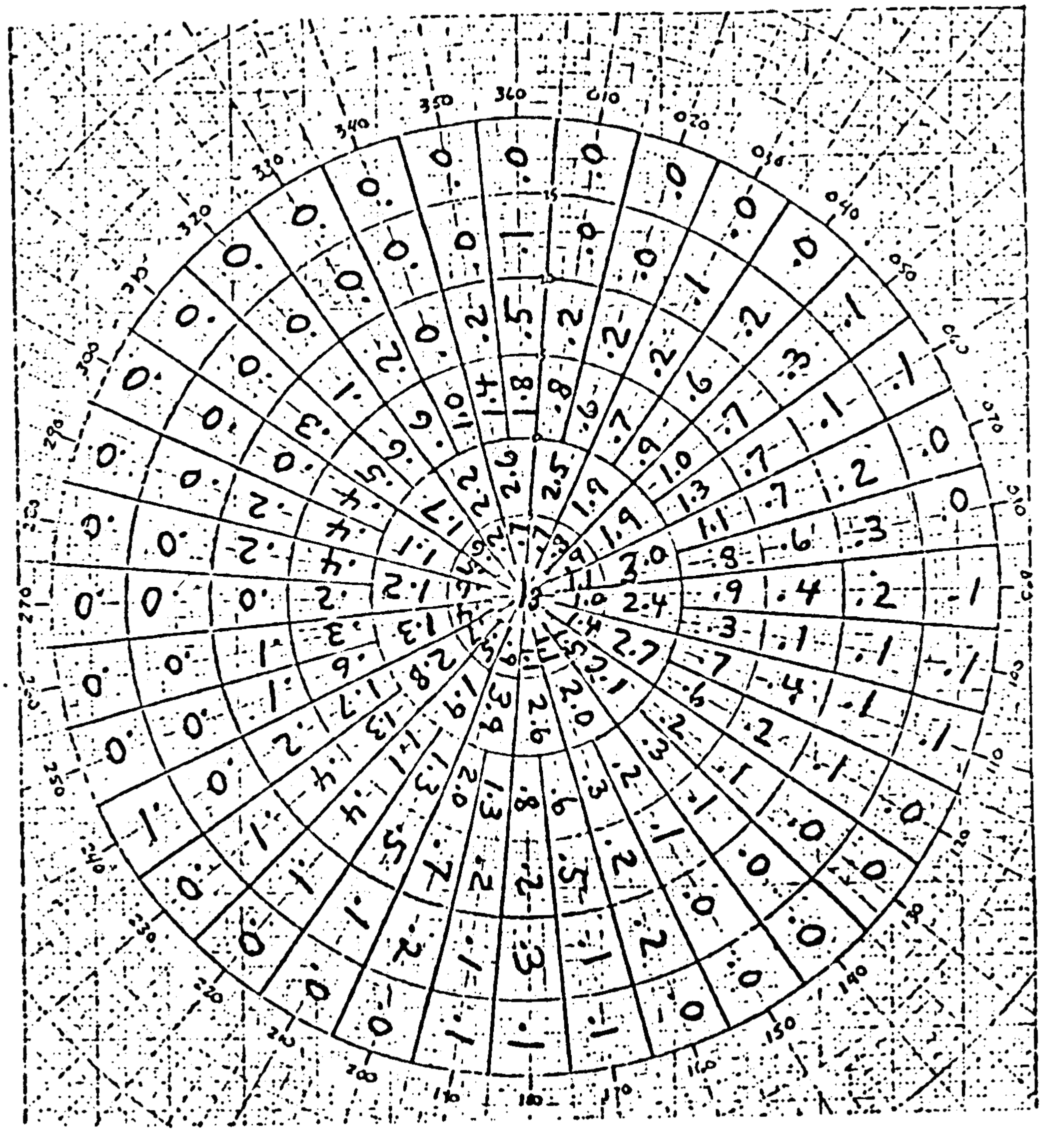


Figure A 3.17

BOSTON-LOGAN WIND ROSE
1972-1978 OBSERVATIONS
0600-2300 LOCAL TIME

Weather Category: IFR-2

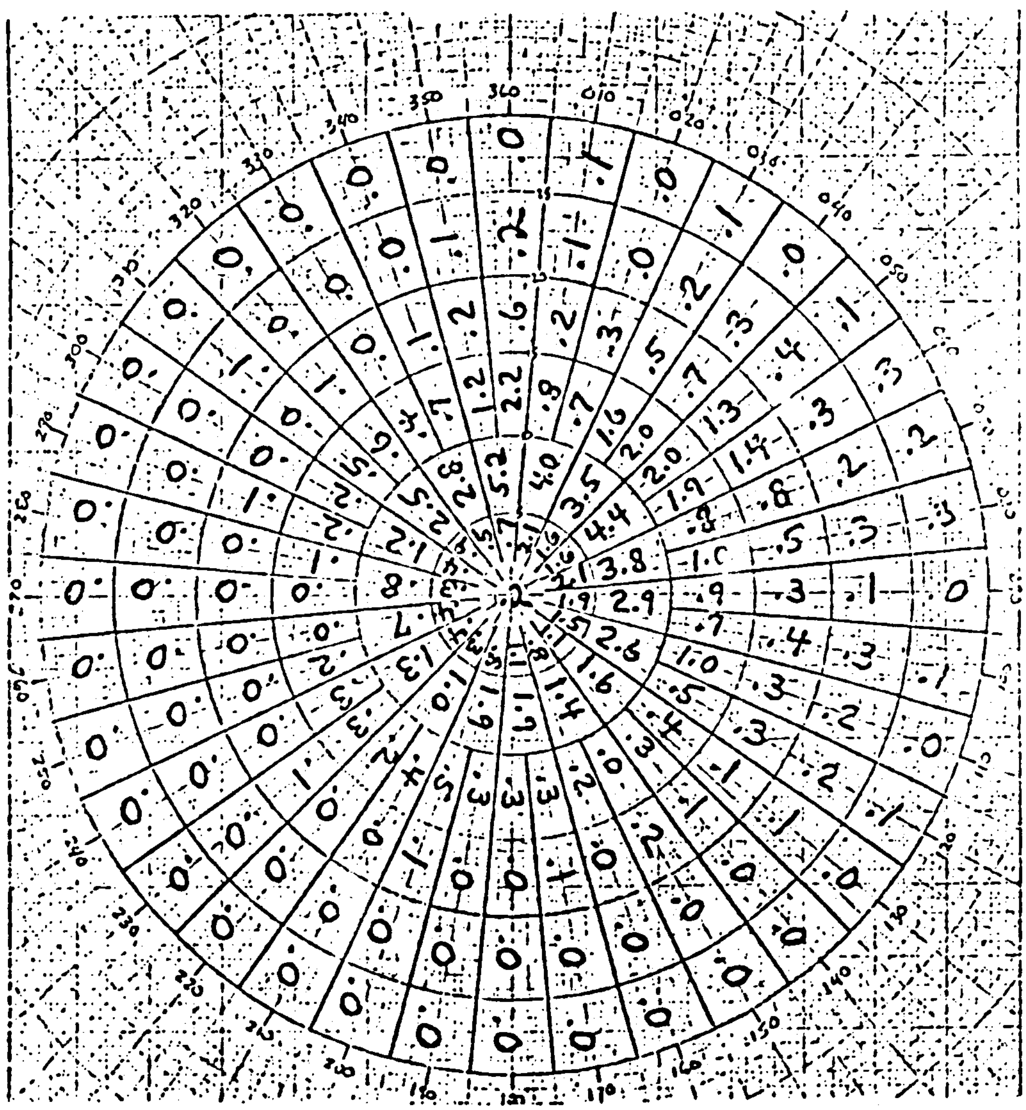
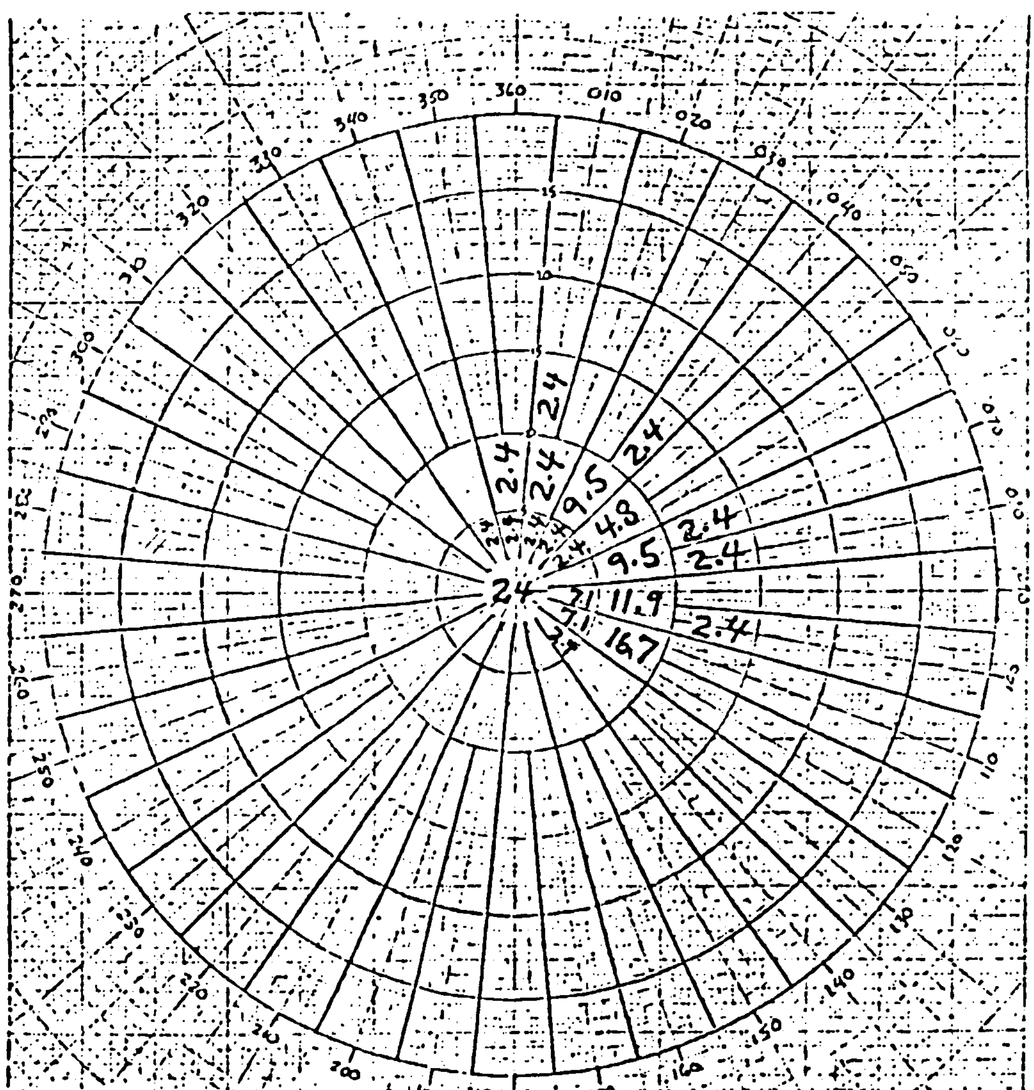


Figure A 3.18

BOSTON-LOGAN WIND ROSE
1972-1978 OBSERVATIONS
0600-2300 LOCAL TIME

Weather Category: IFR-3



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3. FAA, AC-150-5300-4B CHG 6, Appendix 3, "Analyzing Wind Data".

4. FAA, AC-150-5060 CHG.1 (May 1984), "Airport Capacity and Delay".

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FIGURES

PARTS 1 - 3

Figure 1.1 - Geometry for the Opening and Closing Approach Cases

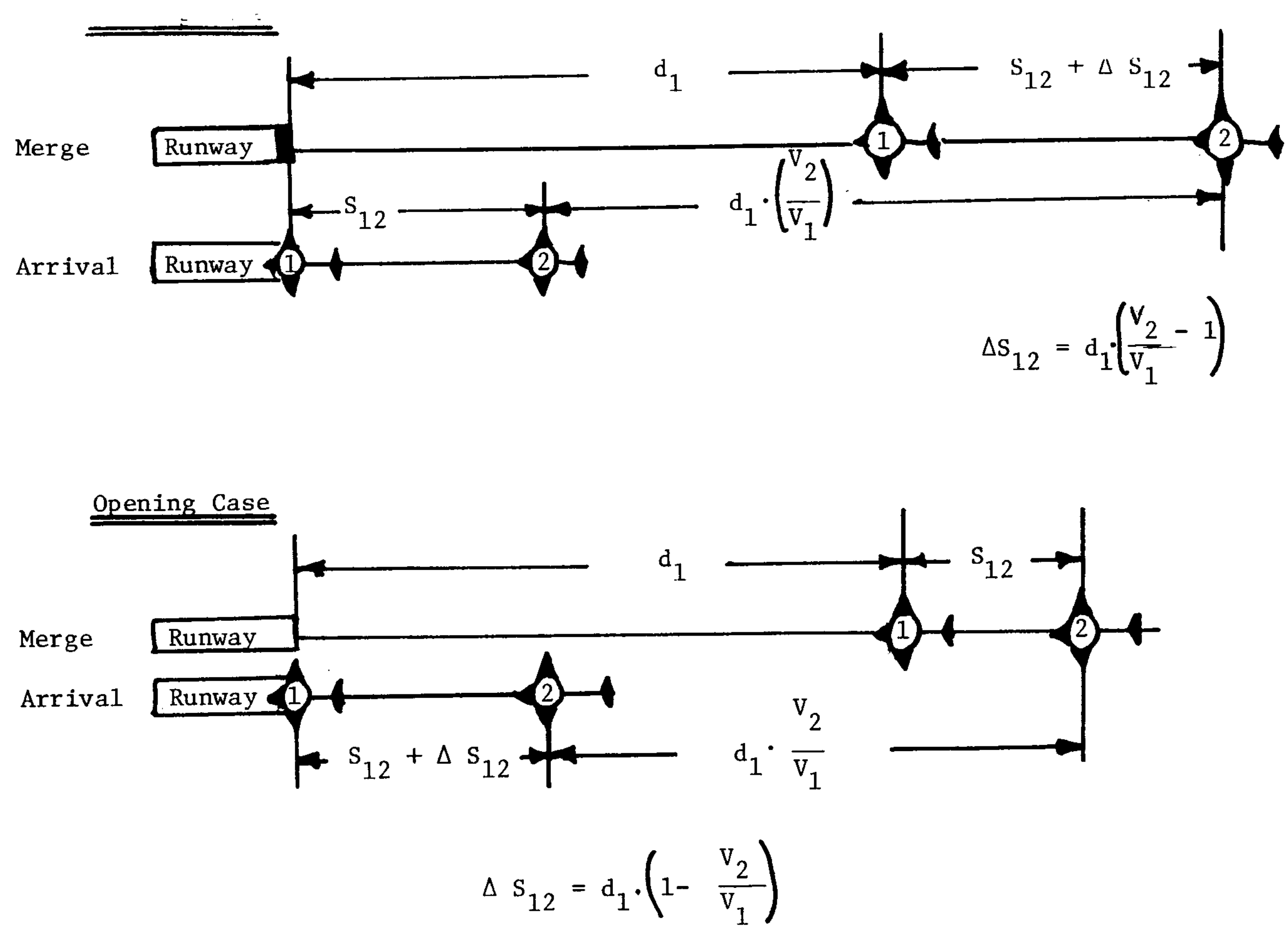

FIGURE 1.2 EFFECT OF INSERTING TAKEOFFS INTO IMC RUNWAY OPERATIONS

EXAMPLE CASE OF SINGLE RUNWAY
{25% HEAVY, 50% LARGE, 25% SMALL
{150KTS, 120KTS, 90KTS

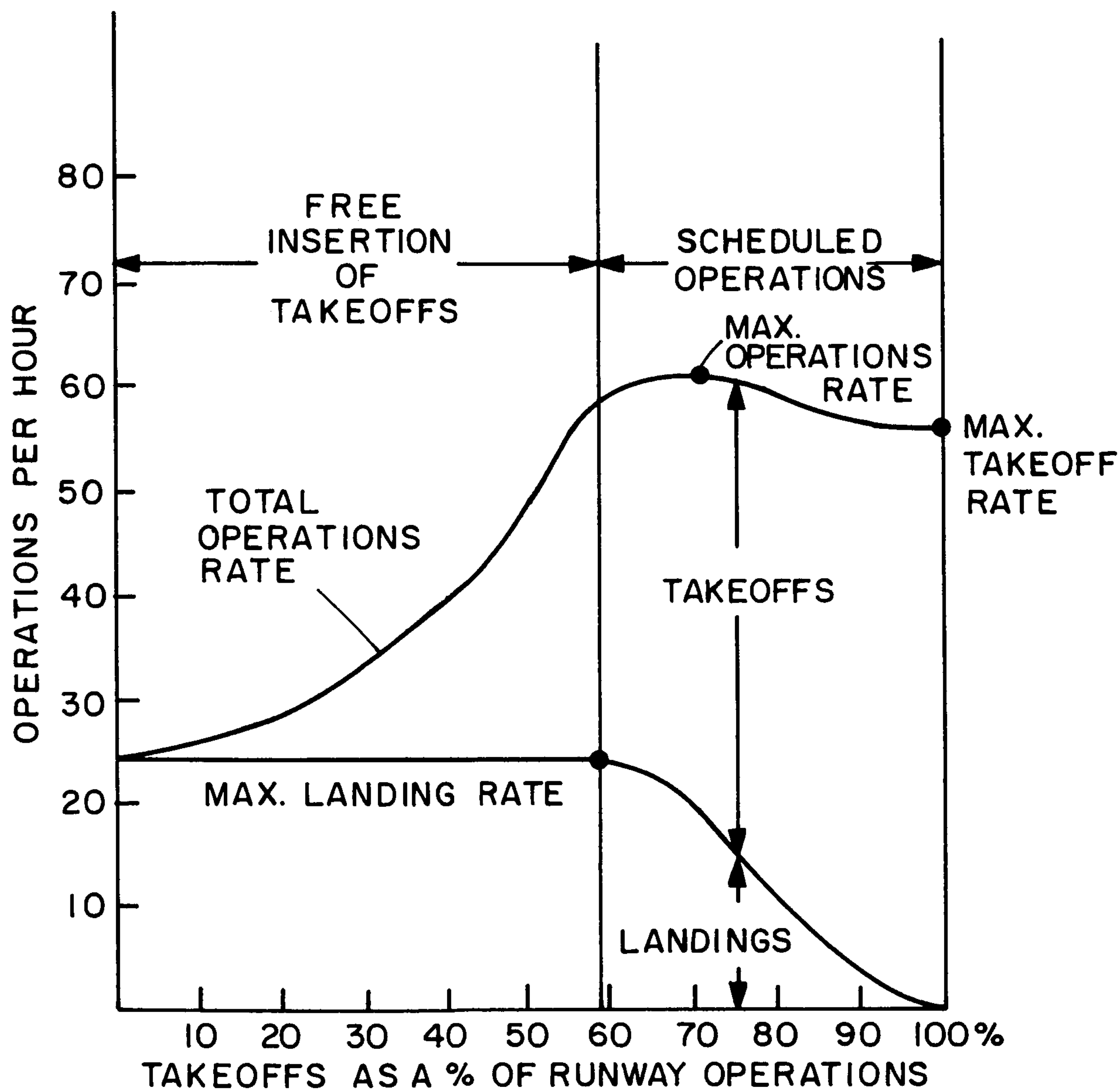

FIGURE 1.3 SIMULTANEOUS INDEPENDENT OPERATIONS OF PARALLEL RUNWAYS
(BY JET TRANSPORT AIRCRAFT)

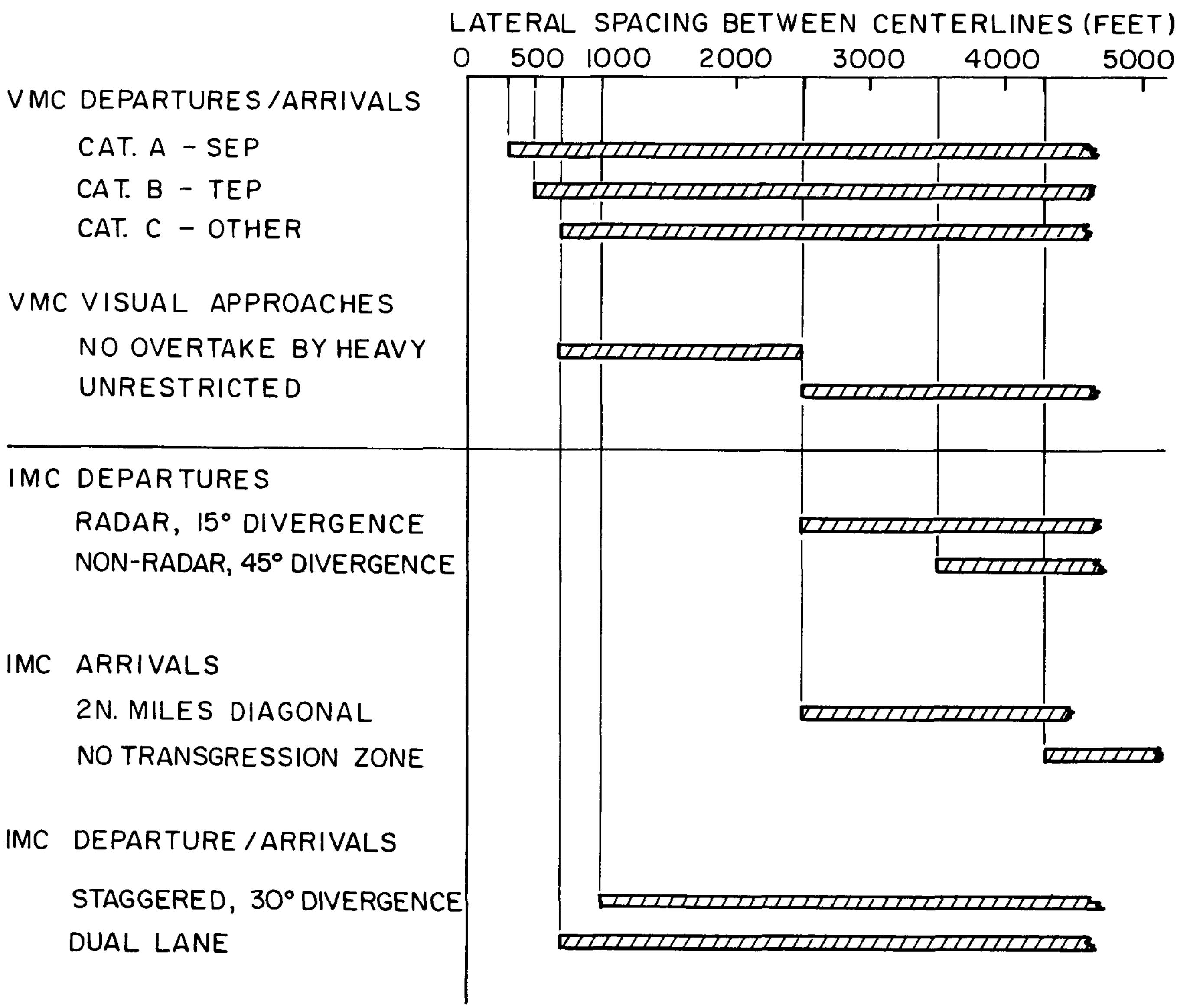

FIGURE 1.4 ALTERNATE APPROACH PATH GEOMETRIES FOR CLOSE PARALLEL RUNWAYS

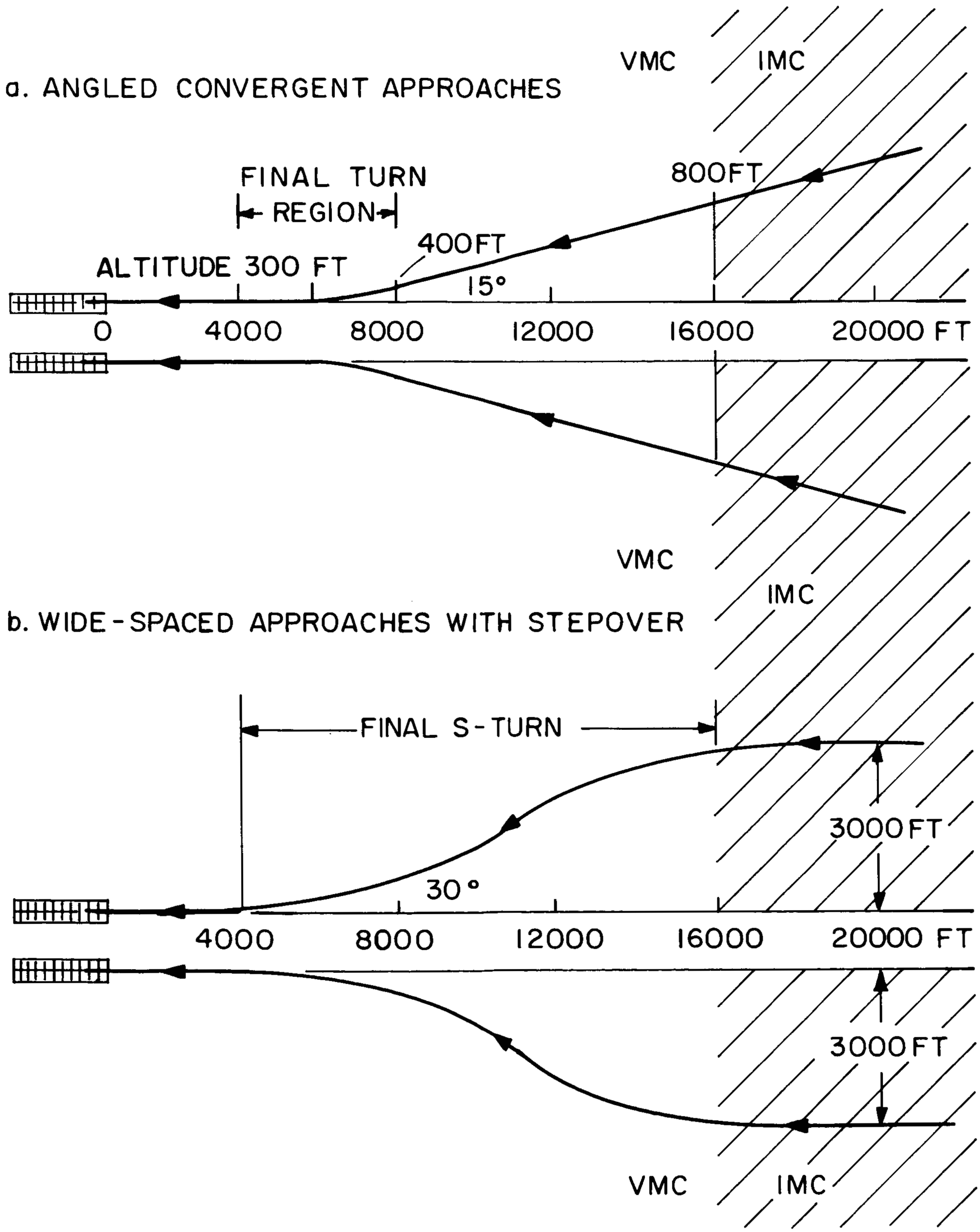

FIGURE 1.5 GEOMETRY OF THE SPLIT APPROACH

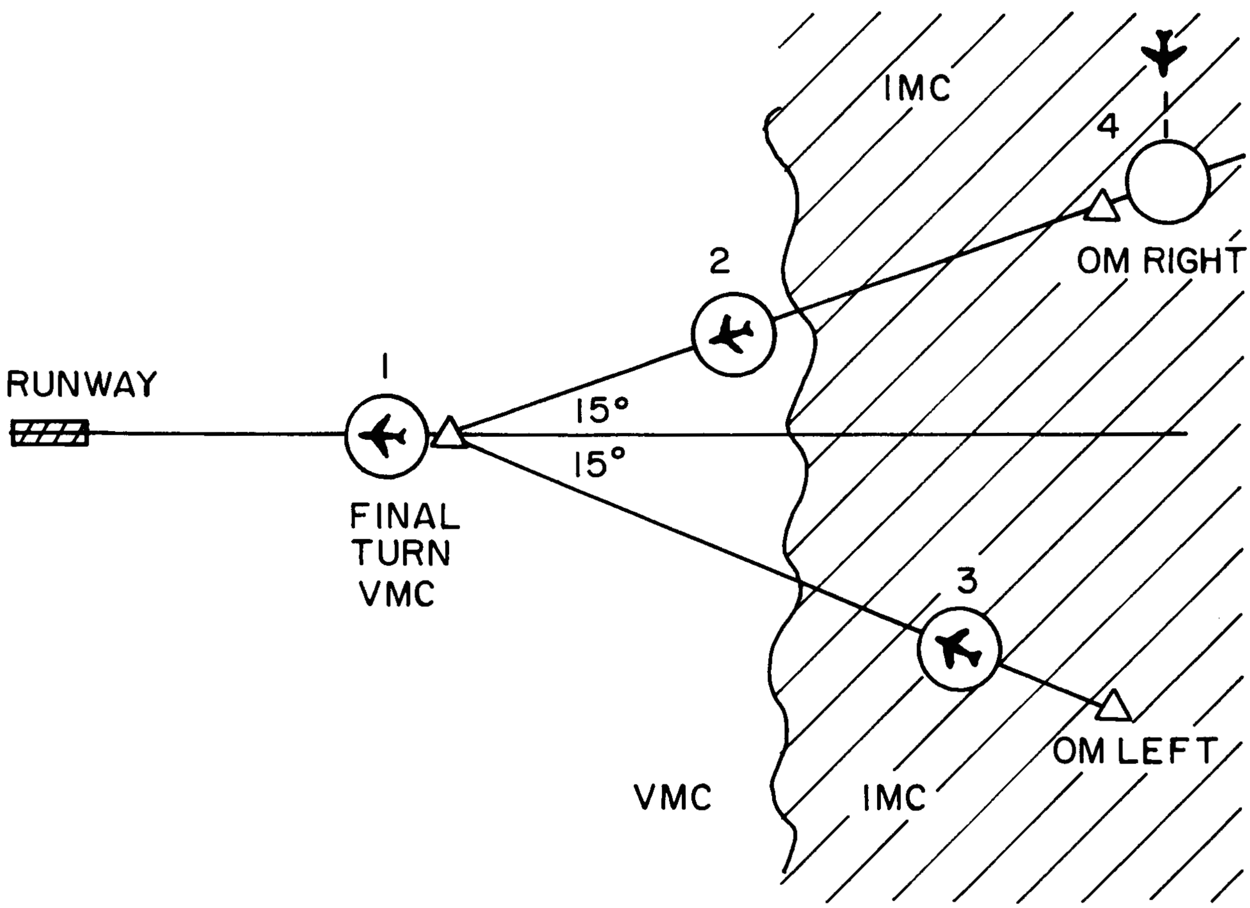

FIGURE 2.1 SEPARATION CRITERIA FOR PARALLEL TRAFFIC UNMONITORED

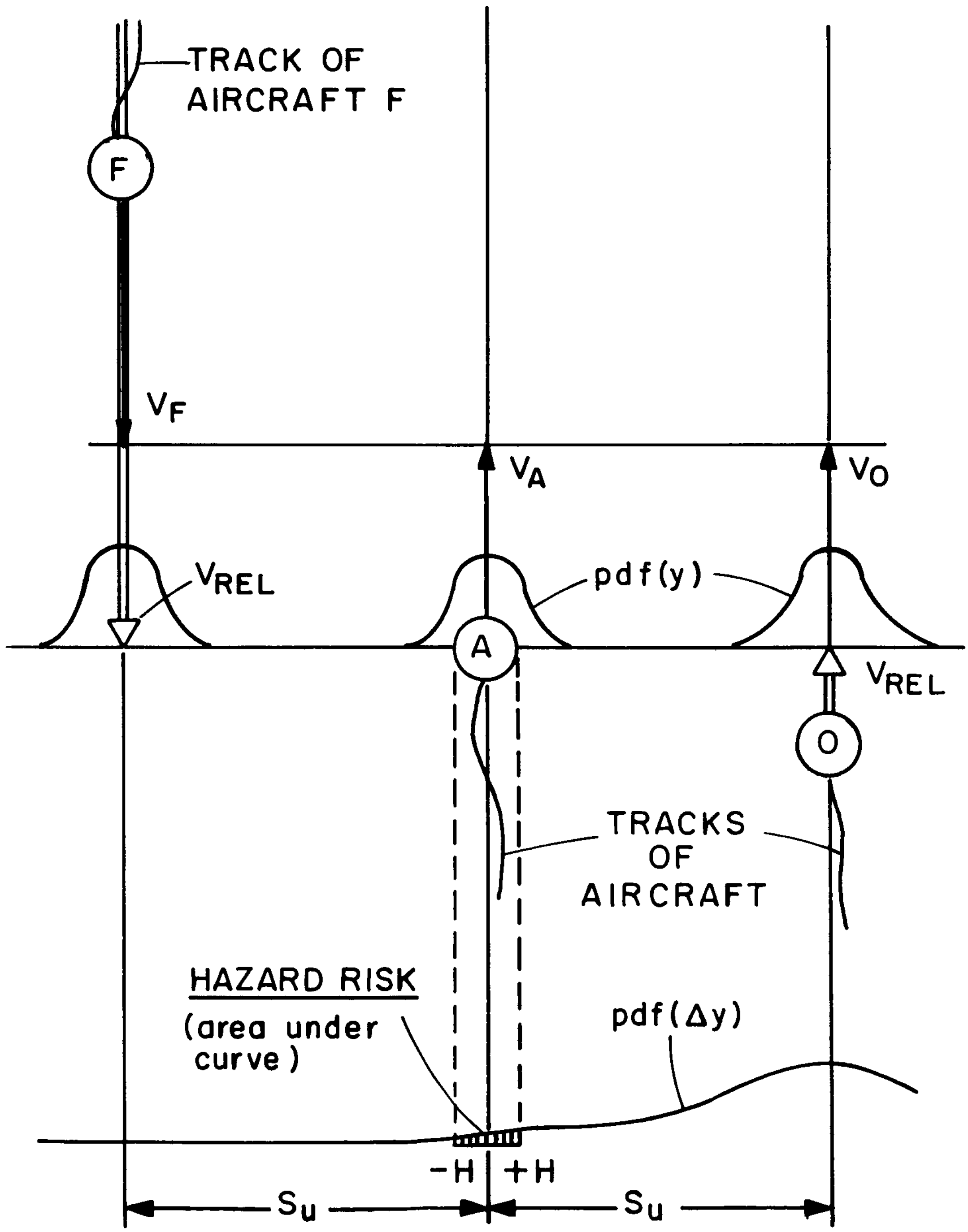

FIGURE 2.2 SEPARATION CRITERIA FOR MONITORED TRAFFIC

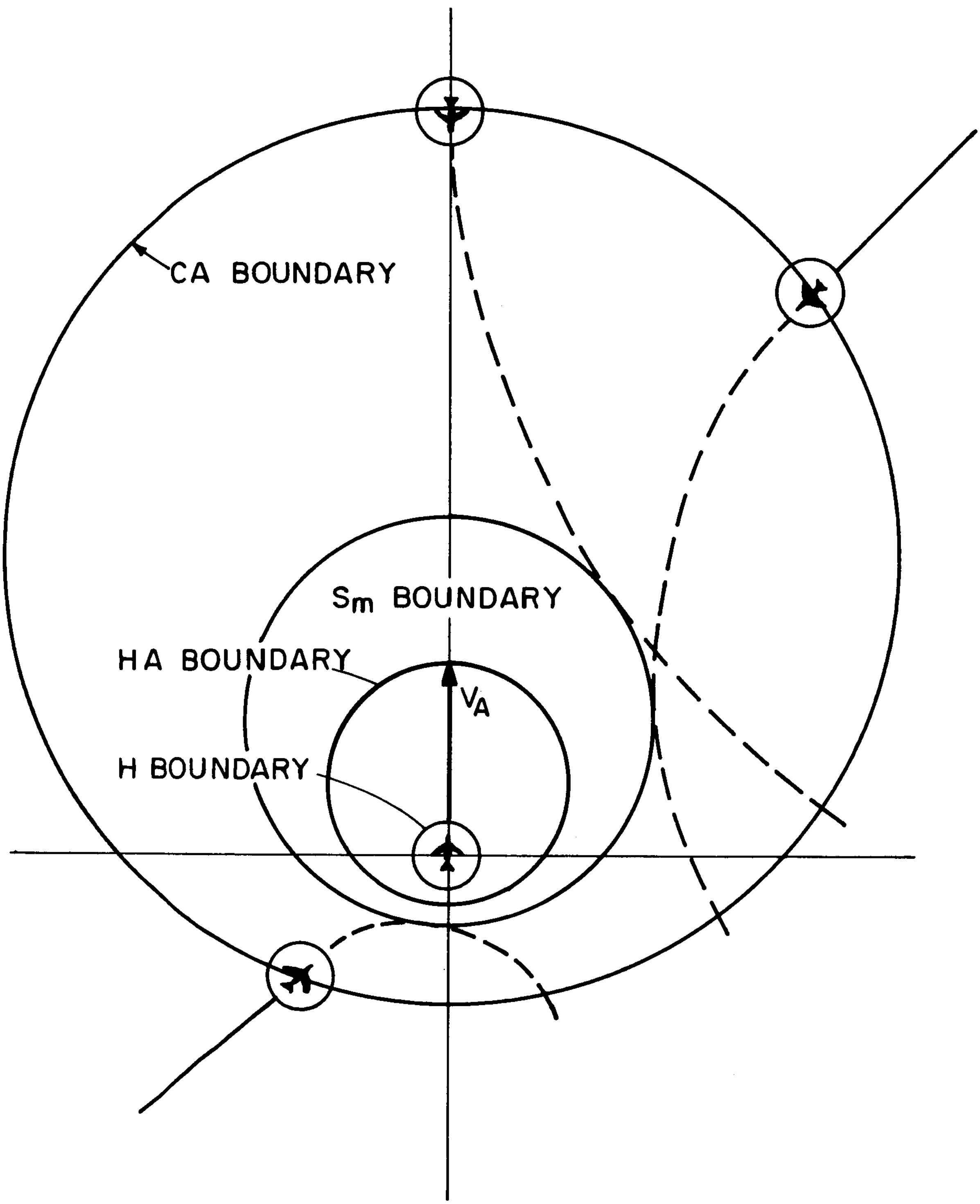

FIGURE 2.3 SEPARATION CRITERIA FOR PARALLEL TRAFFIC MONITORED

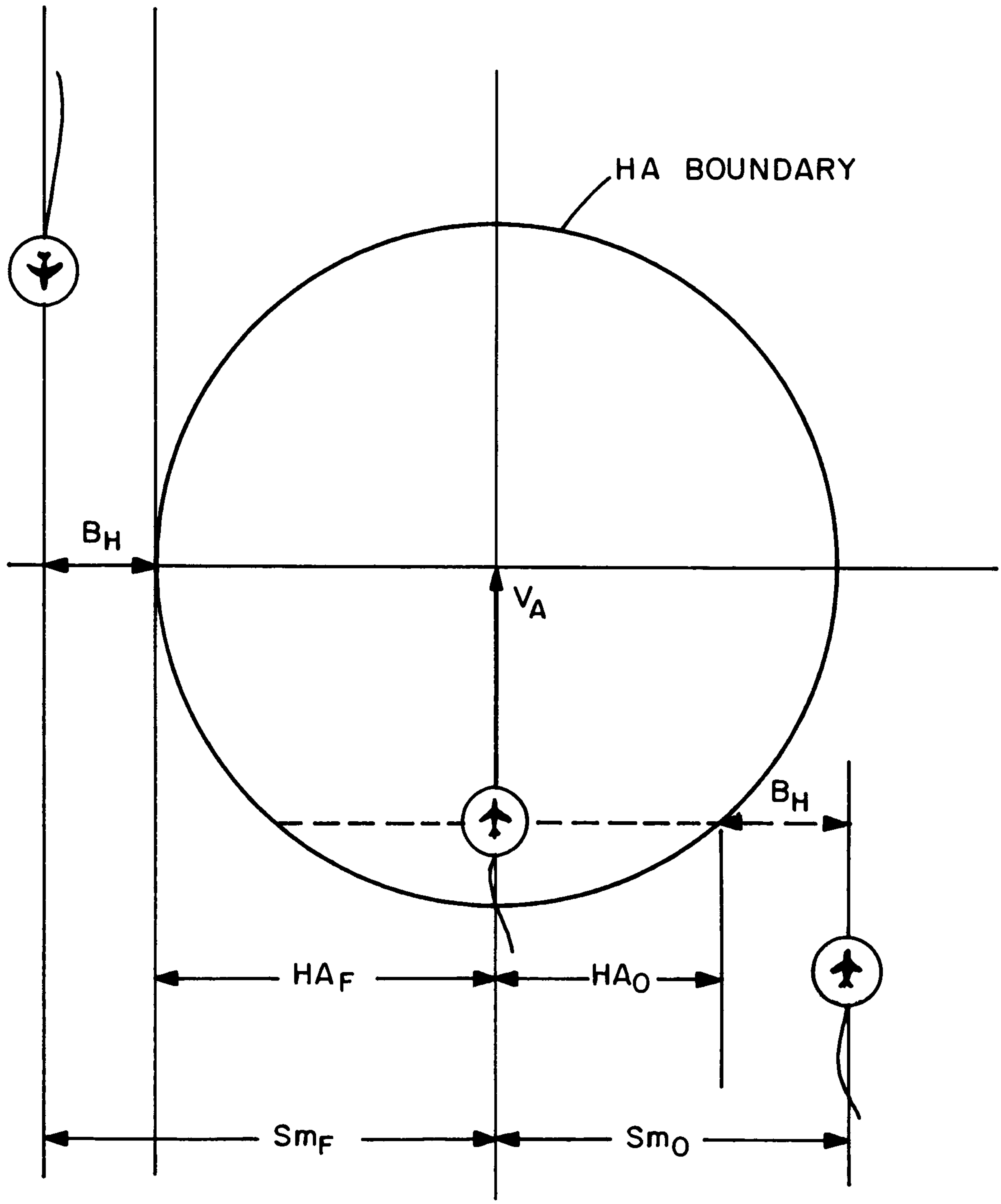

FIGURE 2.4 VIOLATION OF RADAR SEPARATION CRITERIA WITH NO SAFETY RISK

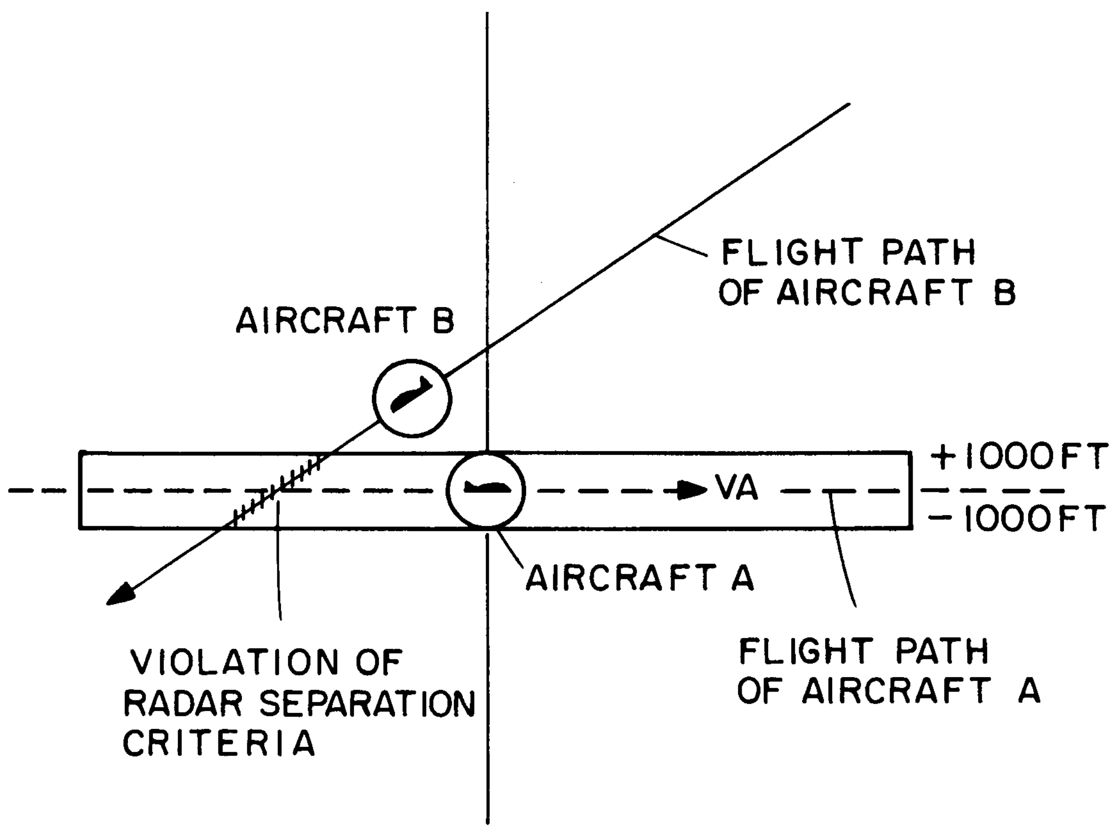

FIGURE 3.1. EXAMPLE OF THE CAPACITY COVERAGE CHART

	CAPACITY	AVAILABILITY	MARGINAL AVAILABILITY
CONFIGURATION A	95	52%	52%
CONFIGURATION B	86	39%	21%
CONFIGURATION C	80	43%	0%
CONFIGURATION D	74	30%	24%

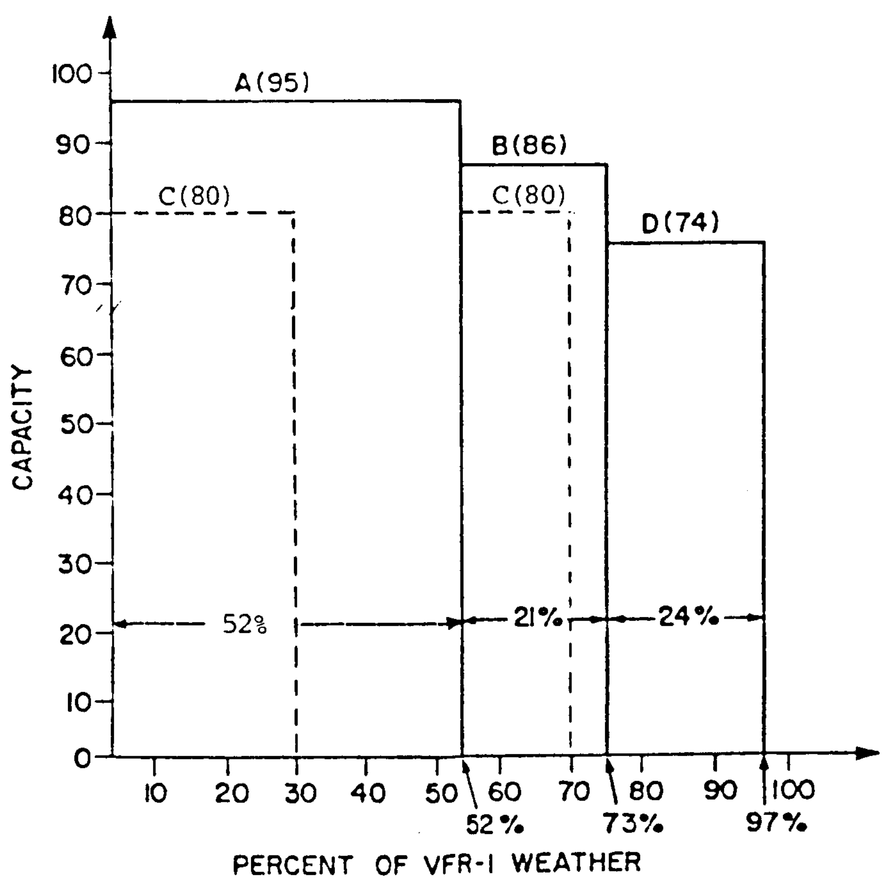

FIGURE 3.2 LAYOUT PLAN
DENVER/STAPLETON INT. AIRPORT

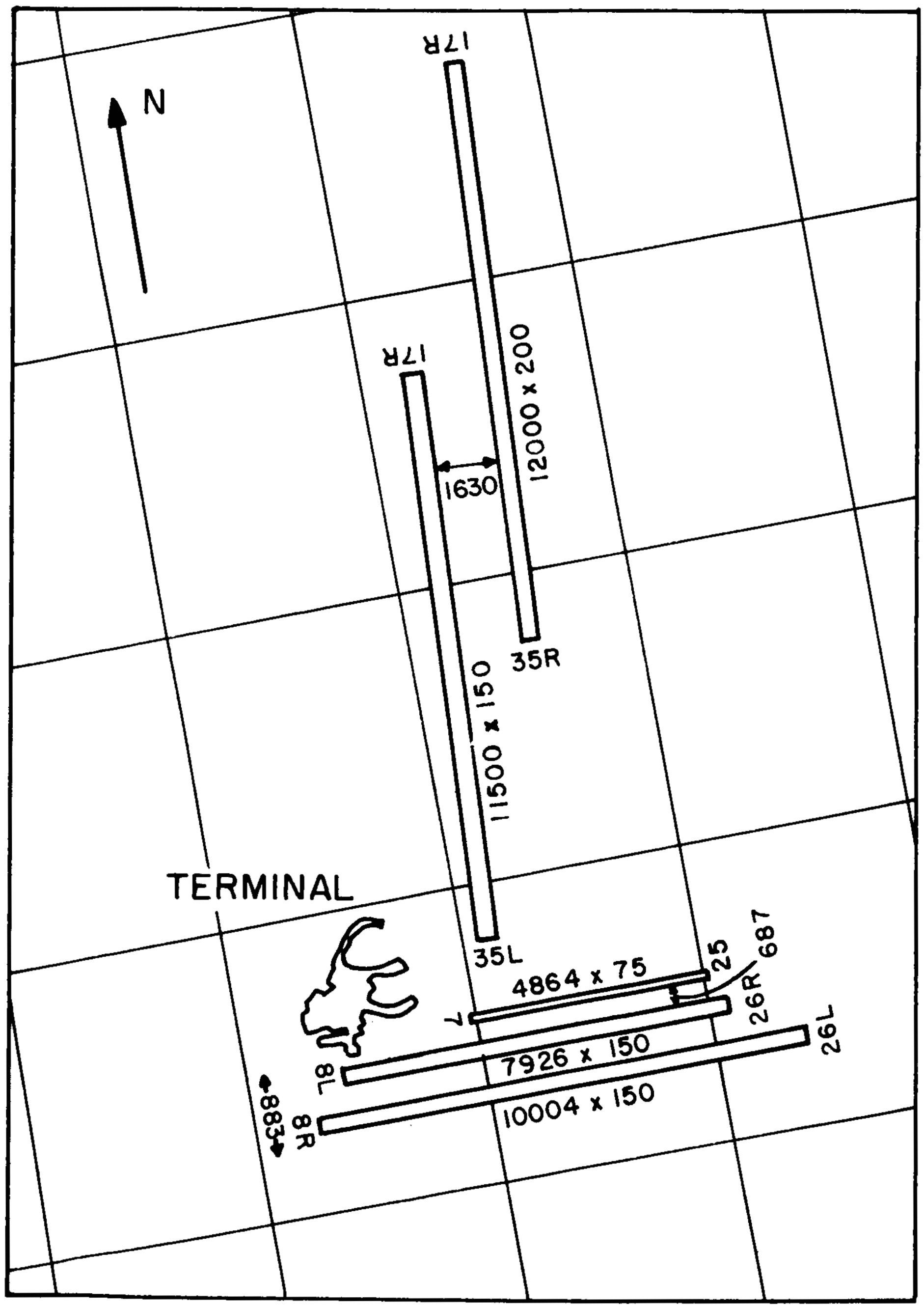

FIGURE 3.3 WEATHER CATEGORIES FOR RUNWAY OPERATIONS AT DENVER STAPLETON

WEATHER	VISIBILITY/CEILING	PERCENTAGE OCCURRENCE
VFR1	Better than 3 miles / 2100 ft	90.0%
VFR2	Less than 3 miles / 2100 ft but better than 3 miles / 1000 ft	4.6%
IFR1	Between 2 miles / 800 ft and 3 miles / 1000 ft	1.4%
IFR2	Operating minimums	4.0%

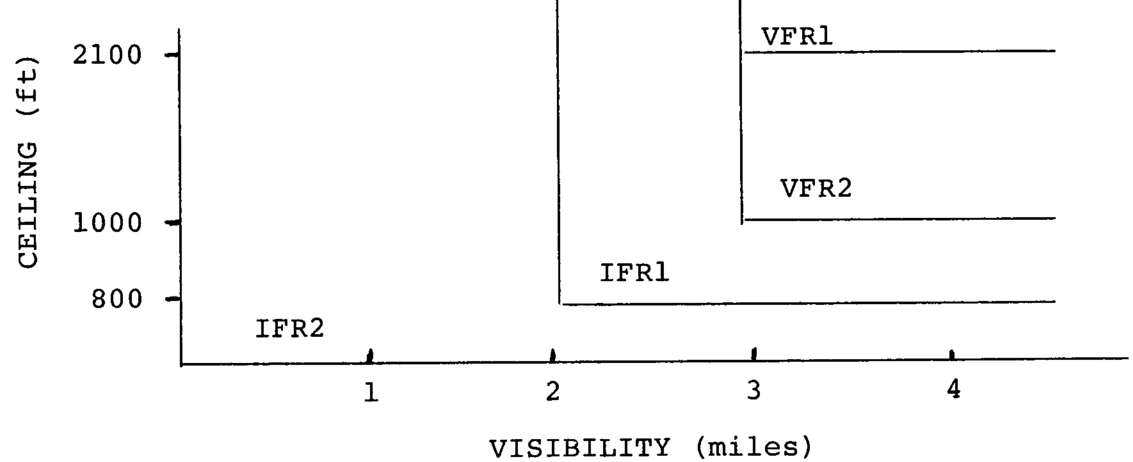

FIGURE 3.4 DENVER STAPLETON RUNWAY CONFIGURATIONS

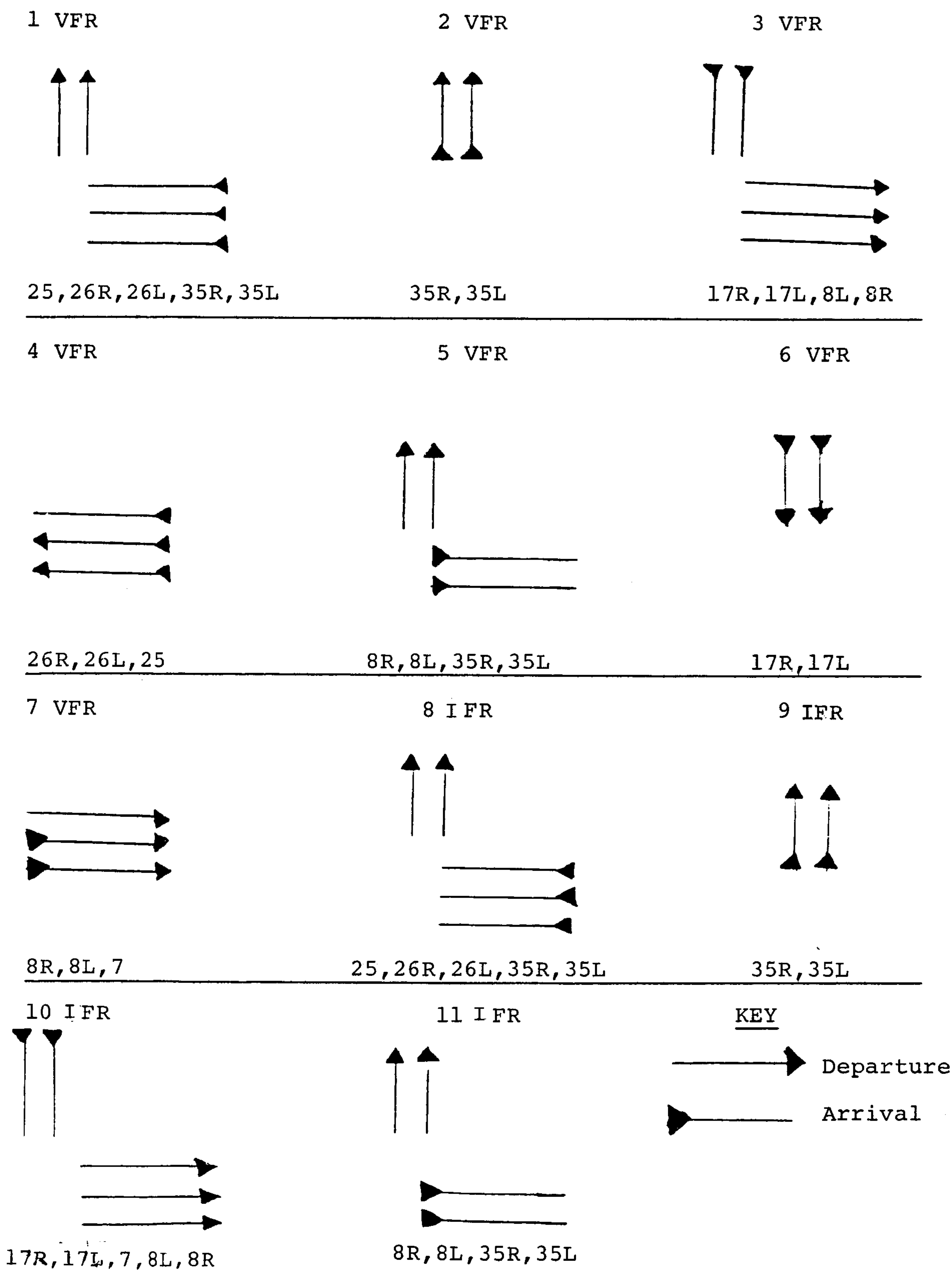

FIGURE 3.5 OPERATIONAL CAPACITIES FOR RUNWAY CONFIGURATIONS AT DENVER STAPLETON

		CAPACITY (OPS/HR)					
CONFIGURATION	RUNWAY IN USE	VFR1	VFR2	VFR	IFR1	IFR2	IFR
1	25, 26R, 26L, 35L, 35R	150	135	149			
2	35L, 35R	98	95	98			
3	17L, 17R, 7, 8L, 8R	125	120	125			
4	26L, 26R, 25	100	--	100			
5	8L, 8R, 35L, 35R	128	121	127			
6	17R, 17L	95	--	95			
7	8R, 8L, 7	--	113	113			
8	25, 26R, 26L, 35L, 35R				61	61	61
9	35L, 35R				61	59	59
10	17L, 17R, 7, 8L, 8R				61	59	60
11	8L, 8R, 35L, 35R				61	59	60

REFERENCE: FAA DELAY TASK FORCE STUDY - MARCH 1980

FIGURE 3.6 DENVER STAPLETON CAPACITY COVERAGE (ALL WEATHER)

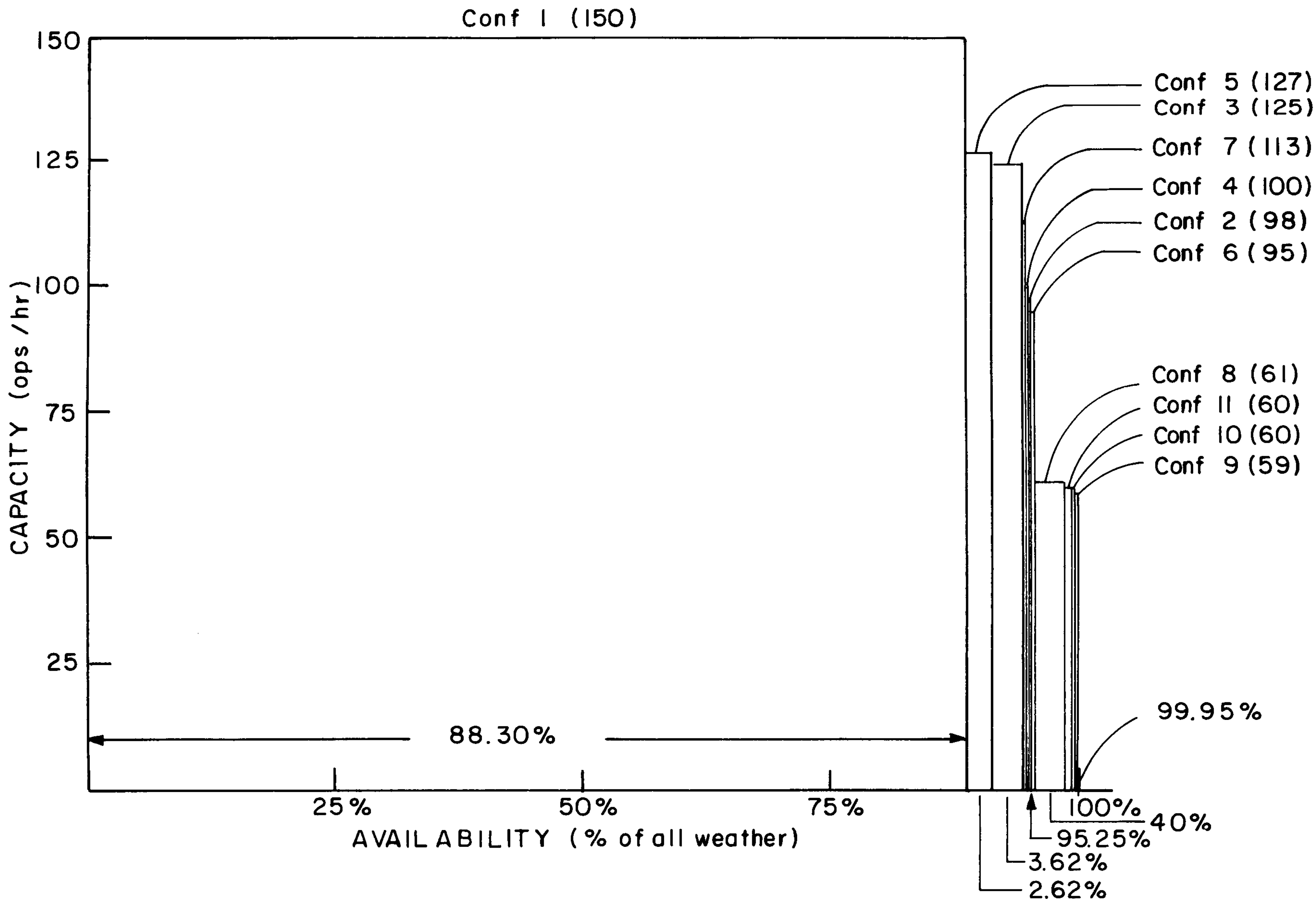

FIGURE 3.7 DENVER STAPLETON IFR CAPACITY COVERAGE
IFR WEATHER = 4.65% annually

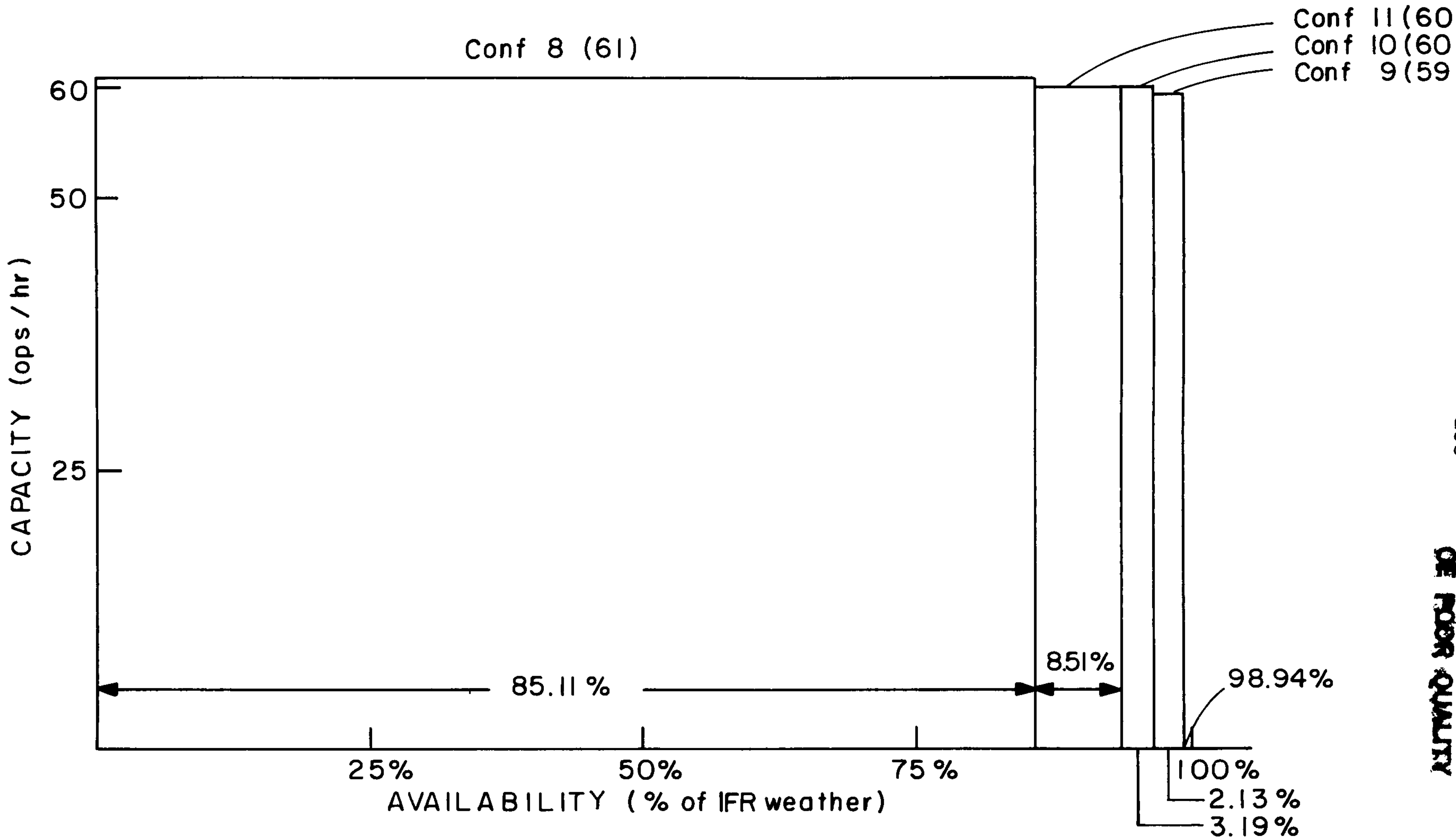

FIGURE 3.8 AIRFIELD OPERATIONS PERCENTAGE USE FOR DENVER STAPLETON, 1980

CONFIGURATION	VFR1	VFR2	VFR	IFR1	IFR2	IFR	Total all weather
1, 8	49.1 %	3.1 %	52.2 %	0.9 %	2.9 %	3.8 %	56.0 %
2, 9	1.1	0.1	1.2	0.1	0.4	0.5	1.7
3, 10	31.3	1.0	32.3	0.2	0.5	0.7	33.0
4	2.0	0.0	2.0	0.0	0.0	0.0	2.0
5, 11	2.7	0.3	3.0	0.2	0.2	0.4	3.4
6	3.8	0.0	3.8	0.0	0.0	0.0	3.8
7	0.0	0.1	0.1	0.0	0.0	0.0	0.1
TOTAL	90.0 %	4.6 %	94.6 %	1.4 %	4.0 %	5.4 %	100.0 %

FIGURE 3.9 RUNWAY LAYOUT PLAN-
BOSTON/LOGAN INTL. AIRPORT

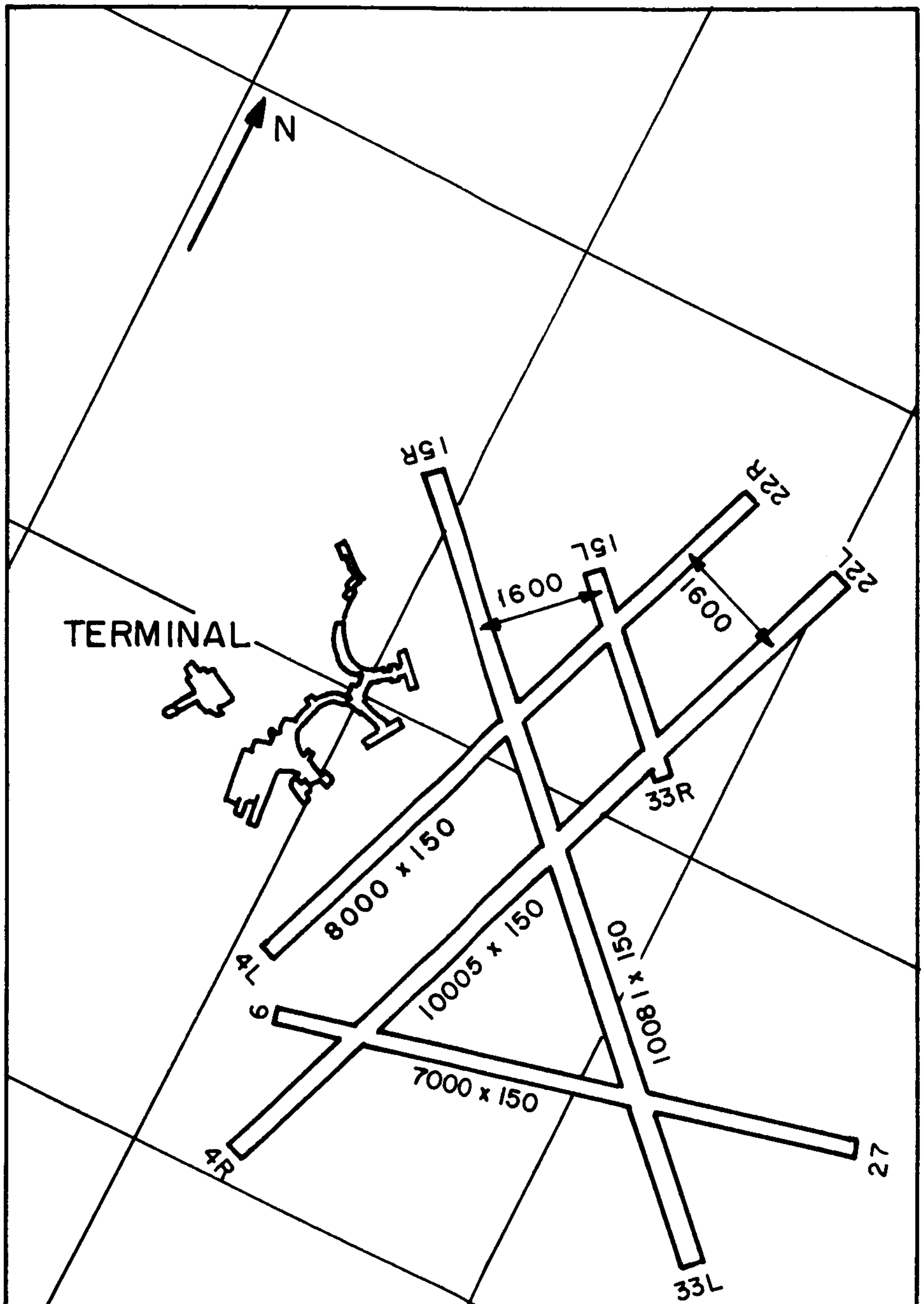

FIGURE 3.10

WEATHER CATEGORIES, BOSTON LOGAN

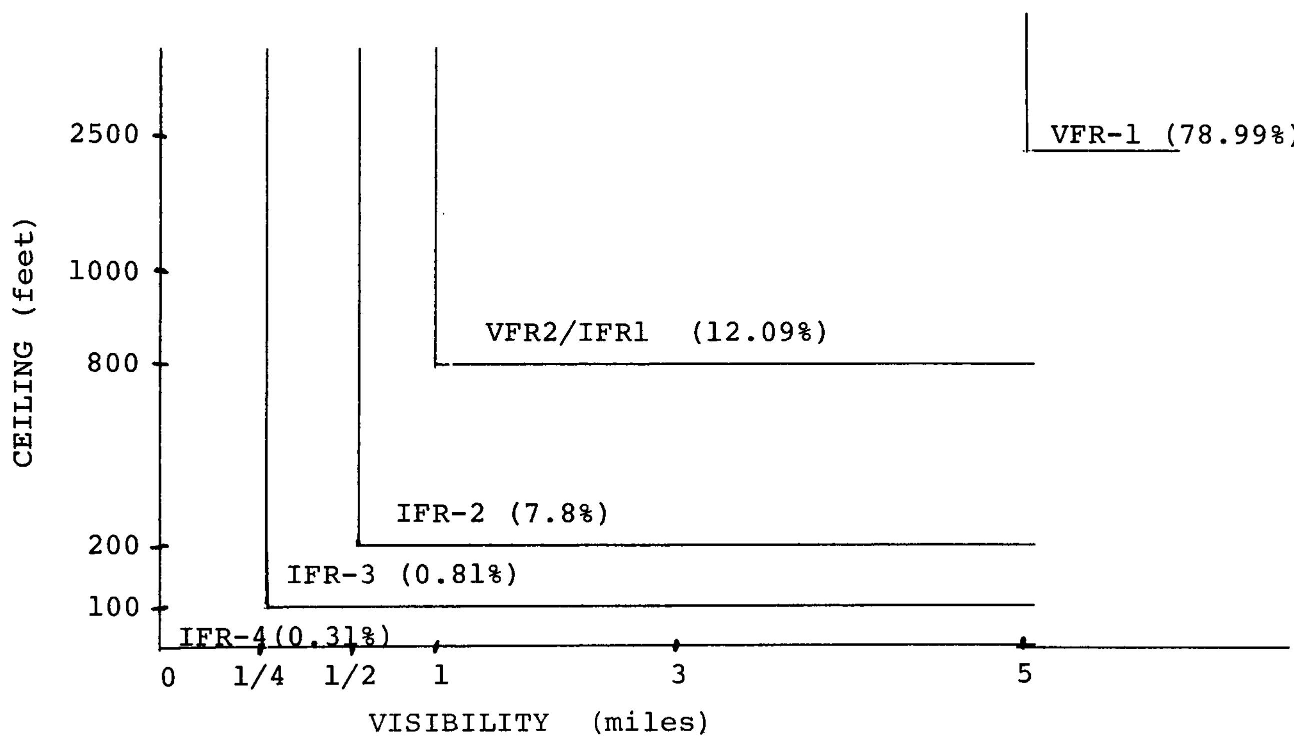

Figure 3.11 - Weather Category Occurrence by Season and Annually at Logan International Airport (in Percent)

Weather Category	Season				Annual
	Spring	Summer	Fall	Winter	
VFR-1	79.19	78.78	80.03	77.94	78.99
VFR-2/IFR-1	10.26	13.86	11.73	12.42	12.07
IFR-2	9.17	6.72	7.42	7.95	7.82
IFR-3	0.72	0.72	1.71	0.18	0.81
IFR-4	0.37	0.22	0.24	0.42	0.31

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FIGURE 3.12. FAA/OSEM CONFIGURATIONS FOR BOSTON LOGAN INTERNATIONAL AIRPORT

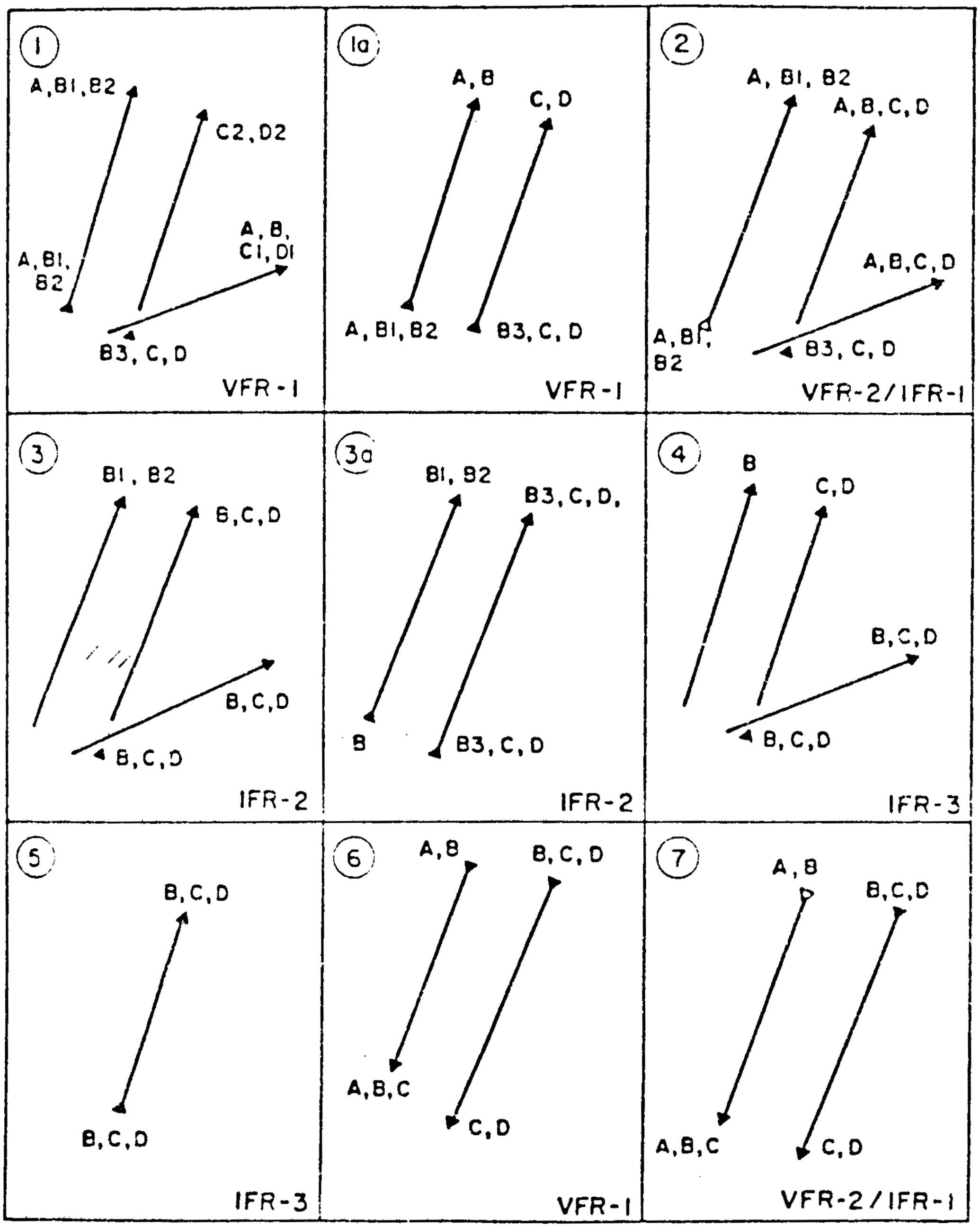

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FIGURE 3.12 (continued) FAA/OSEM CONFIGURATIONS FOR BOSTON LOGAN INTERNATIONAL AIRPORT

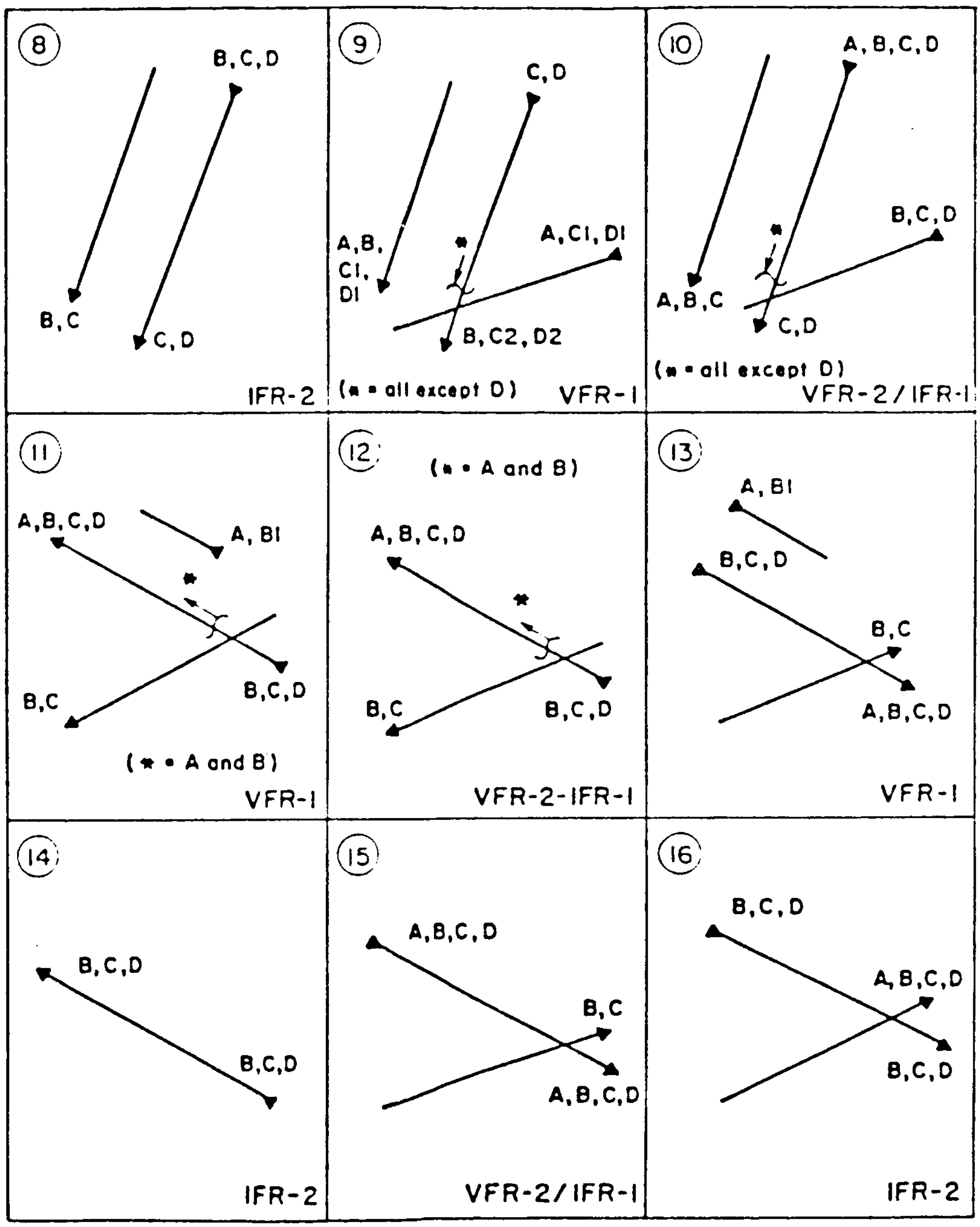


FIGURE 3.12 (continued) FAA/OSEM CONFIGURATIONS FOR BOSTON LOGAN INTERNATIONAL AIRPORT

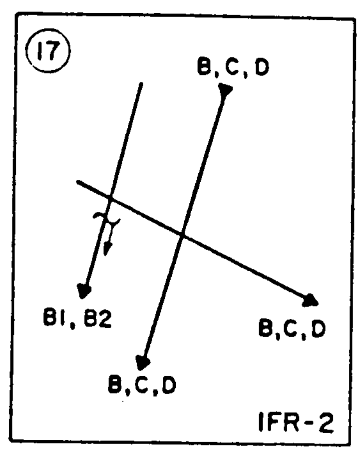


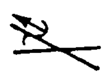
FIGURE 3.13 Key to Symbols

 - Departures

 - Arrivals

 - Arrivals that break away from the main ILS stream at another runway to use this runway.

 - Hold-short arrivals

 - Intersection departures

A, B1, B2, B3, C
C1, C2, D1, D - Aircraft classes (see Figure 3.14)

Figure 3.14. Assumed Aircraft Categories

Class	Description of Aircraft	Approach Speed (knots)	Typical Maximum Takeoff Distance (feet)	Typical Maximum Landing Distance (feet)
A	Single-engine piston	65-95	2,400	2,500
B1	Twin-engine piston	95-105	2,900	3,400
B2	Twin-engine turboprop	105-125	3,300	3,900
B3	Twin-engine turbojet	115-150	5,300	3,200
C	Narrow-body transport	125-135	--	--
D	Wide-body transport	135-145	--	--

FIGURE 3.15

FIXED WING FLEET MIX BY WEATHER CATEGORY
AT LOGAN INTERNATIONAL AIRPORT, 1980
(in Percent)

Weather Category	Aircraft Class A	B1	B2	B3	C	D
VFR-1	6	22	15	3	44	10
VFR-2/IFR-1	3	21	16	3	46	11
IFR-2	0	15	17	4	52	12
IFR-3	0	2	4	4	70	20

Assumptions

VFR-2/IFR-1: 50% of A and 10% of B1 eliminated (relative to VFR-1)

IFR-2: 100% of A, 35% of B1, 10% of B2 eliminated (relative to VFR-1)

IFR-3: 100% of A, 95% of B1, 85% of B2, 20% of B3, 100% of C eliminated (relative to VFR)

NOTE: The fixed wing fleet includes all aircraft except helicopters.

Figure 3.16 - Configuration Capacities (Operations per Hour) at Logan International Airport

Configuration	Weather	Runway Use		% Arrivals		
		Arrive	Depart	40%	50%	60%
1	VFR-1	4L, 4R	4L, 4R, 9	120	111	96
2	VFR-2/IFR-1	4L, 4R	4L, 4R, 9	80	64	53
3	IFR-2	4L, 4R	4L, 4R, 9	70	58	48
4	IFR-3	4L, 4R	4L, 4R, 9	69	58	49
5	IFR-3	4R	4R	49	54	47
6	VFR-1	22L, 22R	22L, 22R	108	107	91
7	VFR-2/IFR-1	22L, 22R	22L, 22R	84	67	56
8	IFR-2	22L	22L, 22R	72	58	48
9	VFR-1	22L, 27	22L, 22R	101	110	114
10	VFR-2/IFR-1	22L, 27	22L, 22R	119	95	79
11	VFR-1	33L, 33R	27, 33L*	83	76	68
12	VFR-2/IFR-1	33L	27, 33L*	69	55	46
13	VFR-1	15L, 15R*	9, 15R*	70	70	65
14	IFR-2	33L	33L	57	54	47
15	VFR-2/IFR-1	15R*	9, 15R*	68	57	48
16	IFR-2	15R	9, 15R	57	54	48
17	IFR-2	22L	15R, 22R*	72	58	48

* Intersection departures on this runway (light aircraft only)

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FIGURE 3.17. COVERAGE CHART: VFR-1 (79%) AT BOSTON LOGAN

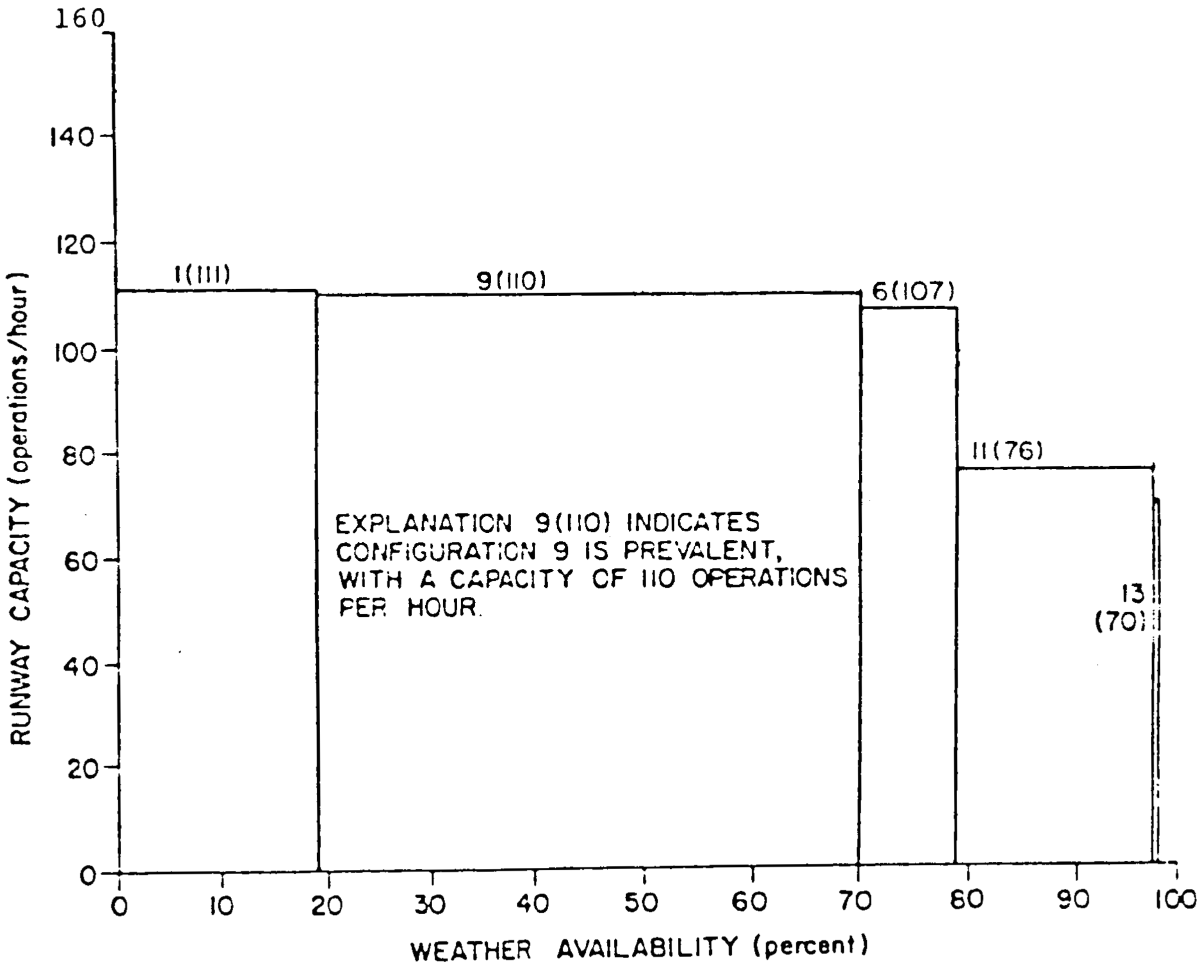


FIGURE 3.18. COVERAGE CHART: VFR-2/IFR-1 (12.2%) AT BOSTON LOGAN

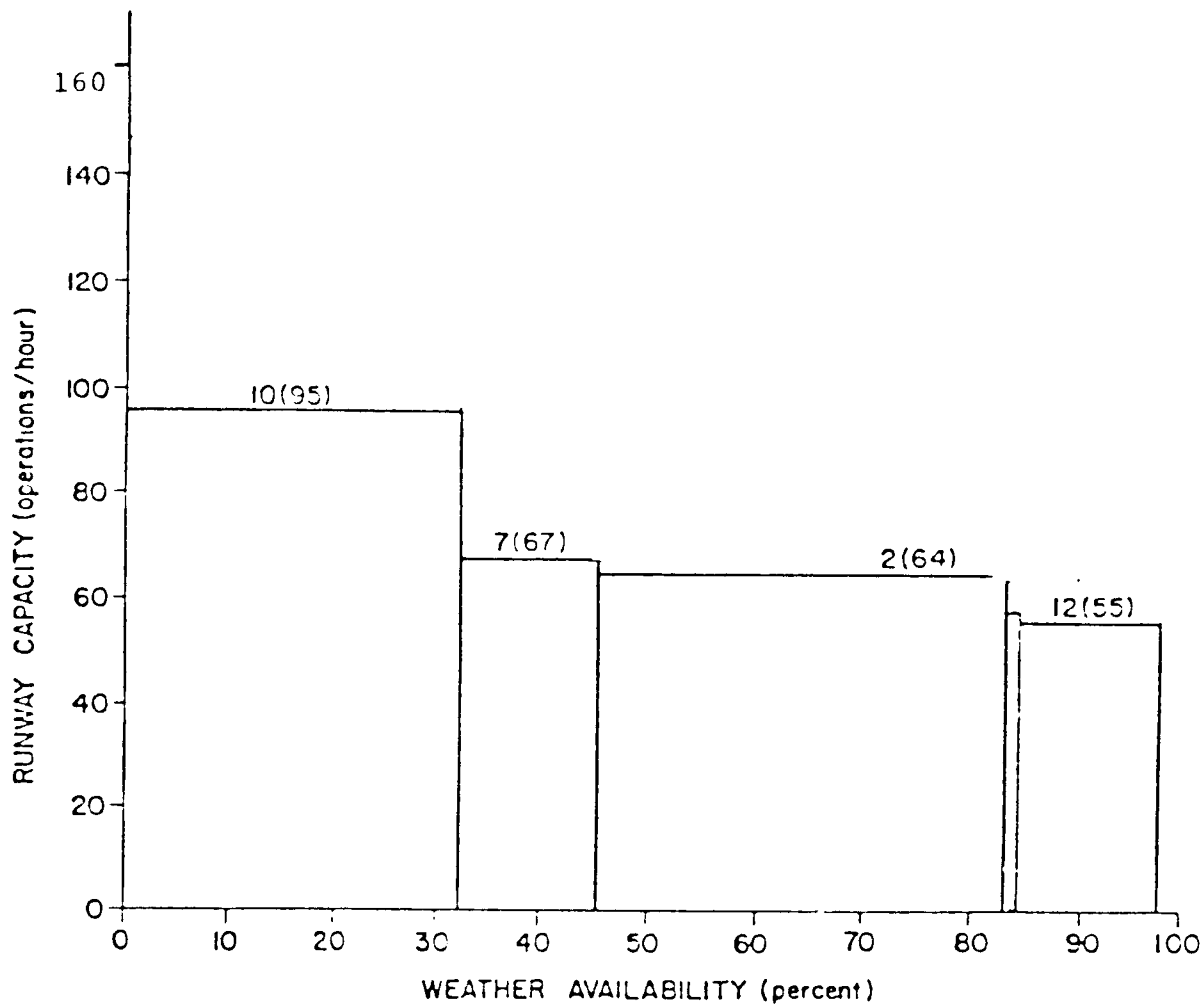


FIGURE 3.19. COVERAGE CHART: IFR-2 (7.8%) AT BOSTON LOGAN

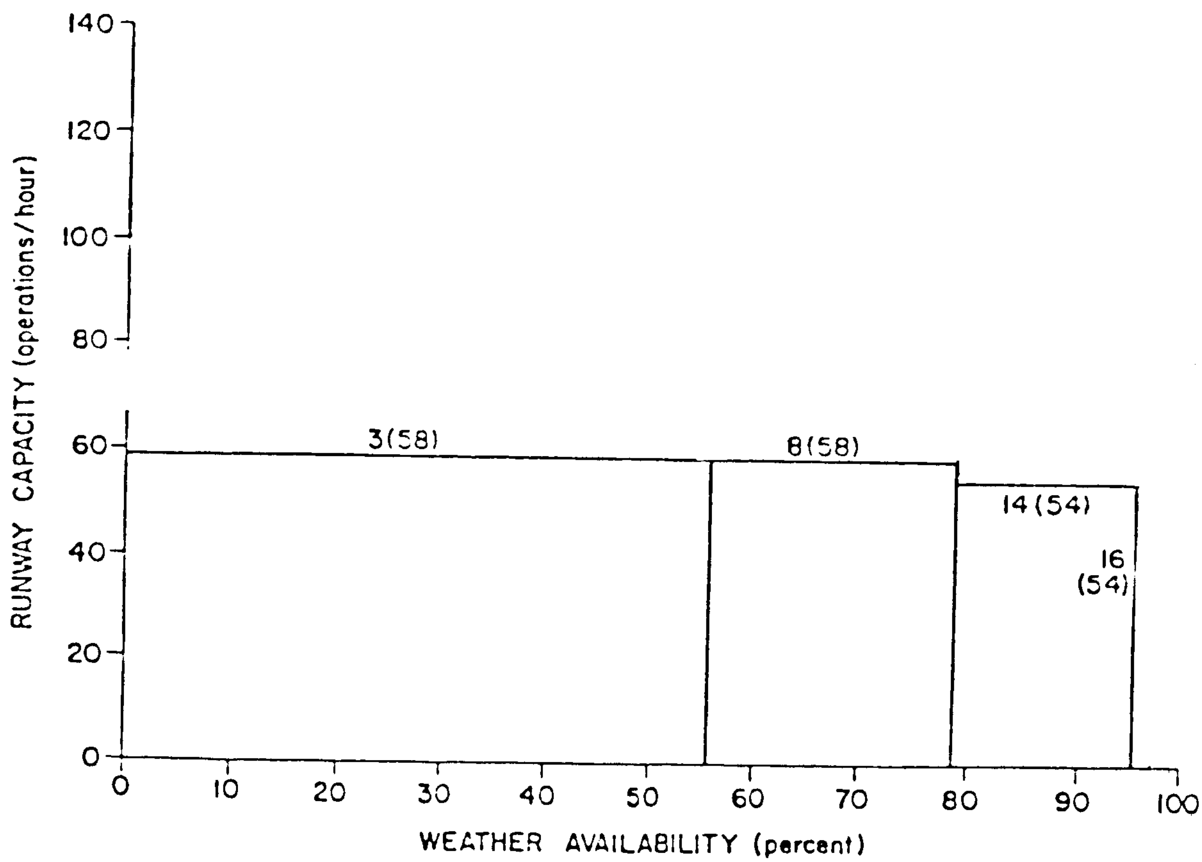


FIGURE 3.20. COVERAGE CHART: IFR-3 (0.81%) AT BOSTON LOGAN

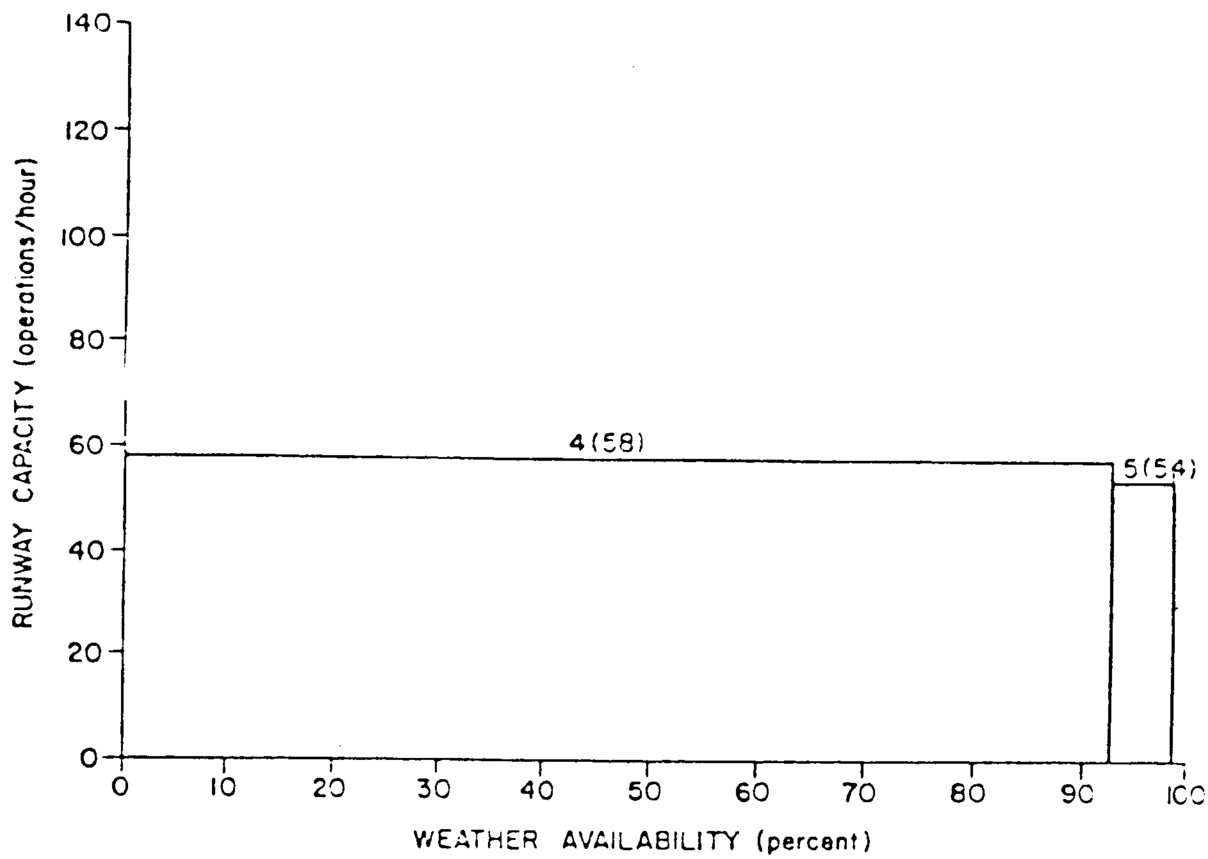


FIGURE 3.21 DENVER STAPLETON CAPACITY COVERAGE (ALL WEATHER)

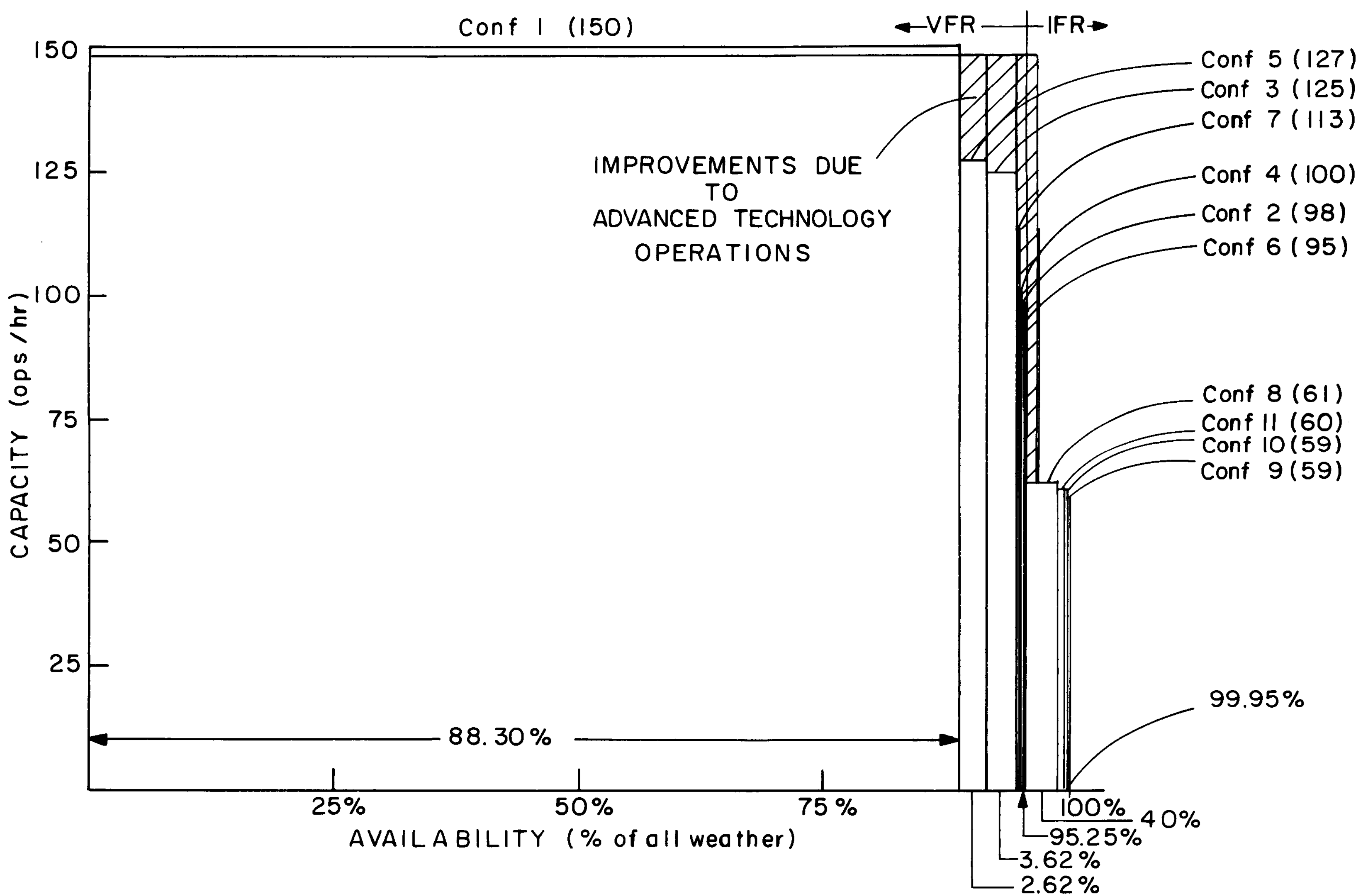


FIGURE 3.22. COVERAGE CHART WITH ADVANCED TECHNOLOGY: VFR-1 (79%) AT BOSTON LOGAN

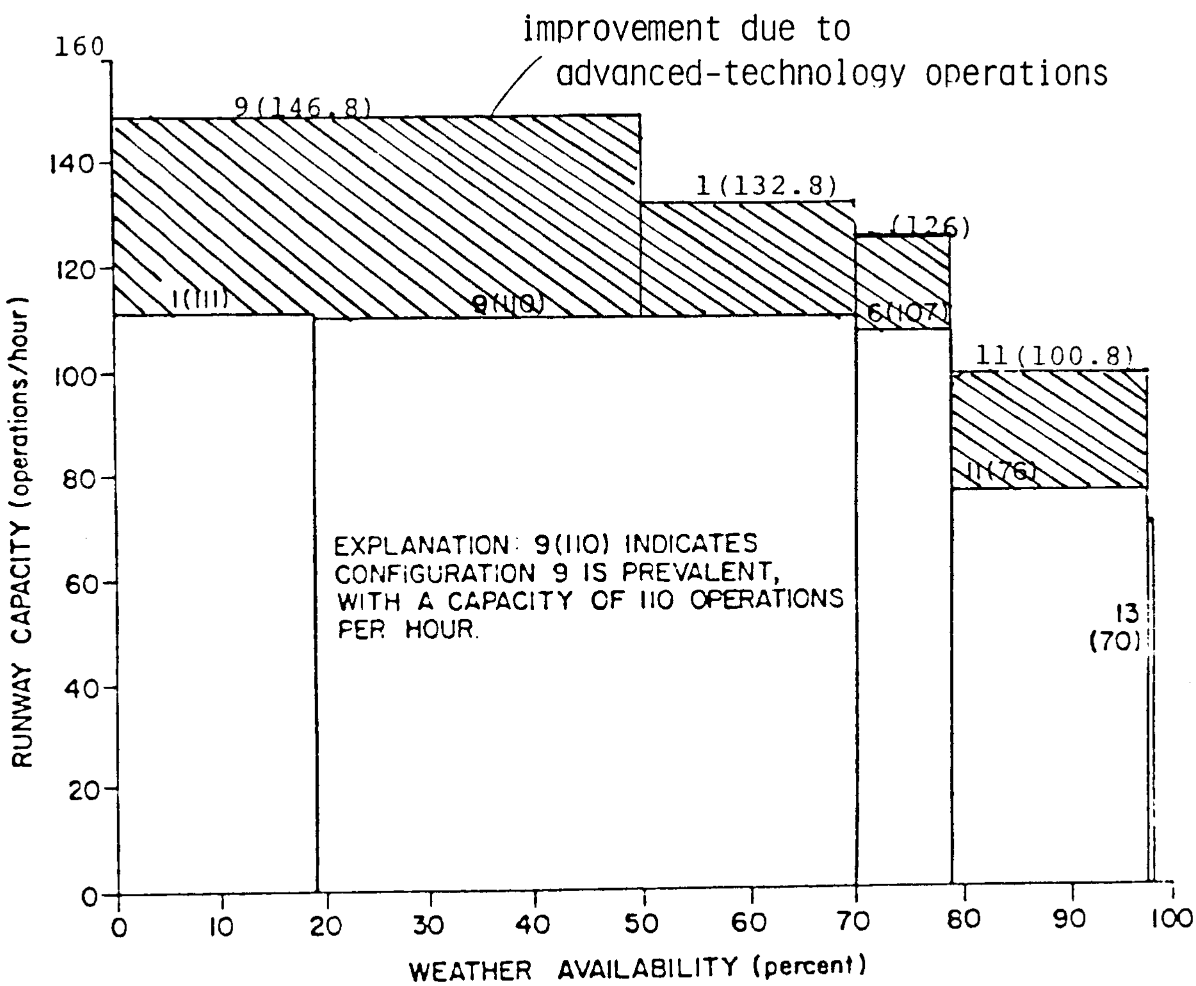


FIGURE 3.23. COVERAGE CHART WITH ADVANCED TECHNOLOGY: VFR-2/IFR-1 (12.2%) AT BOSTON LOGAN

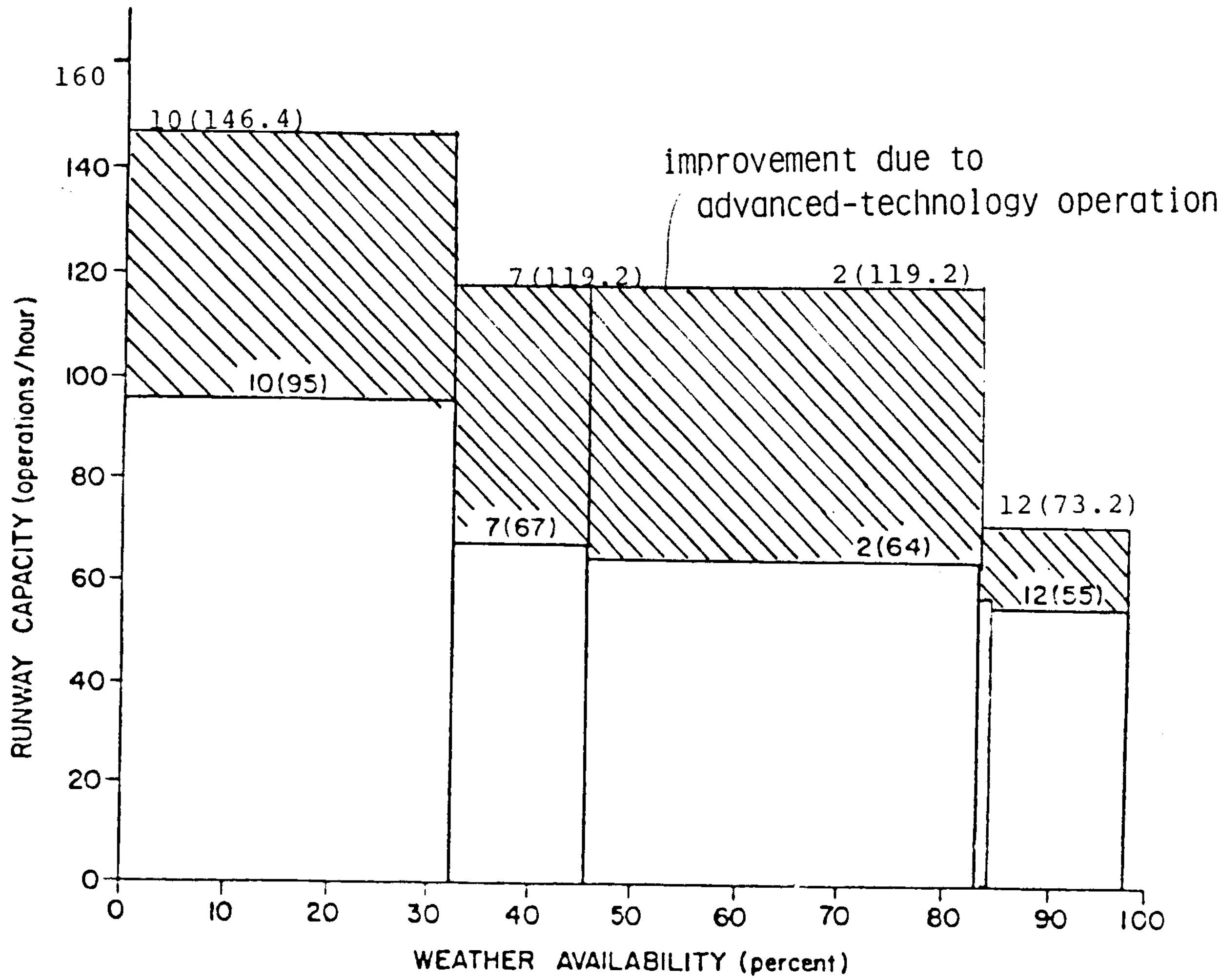


FIGURE 3.24. COVERAGE CHART WITH ADVANCED TECHNOLOGY:
IFR-2 (7.8%) AT BOSTON LOGAN

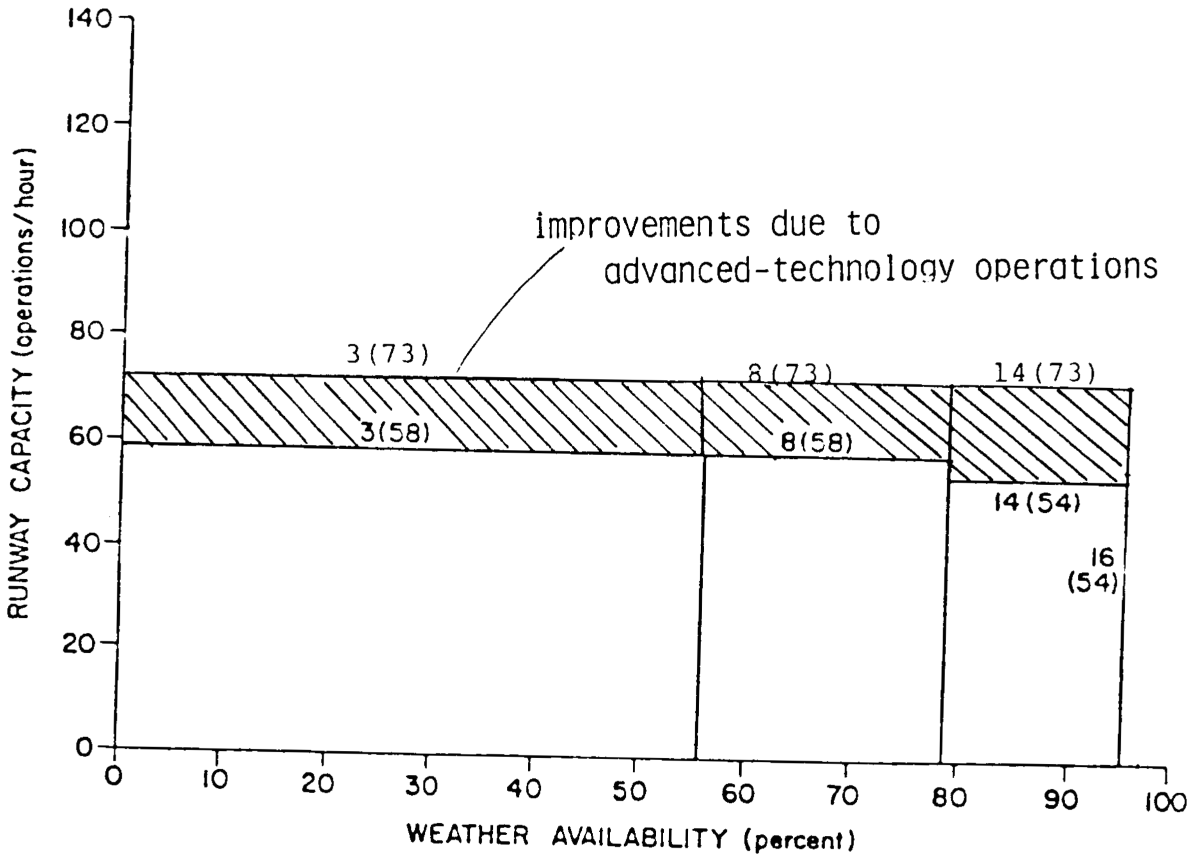
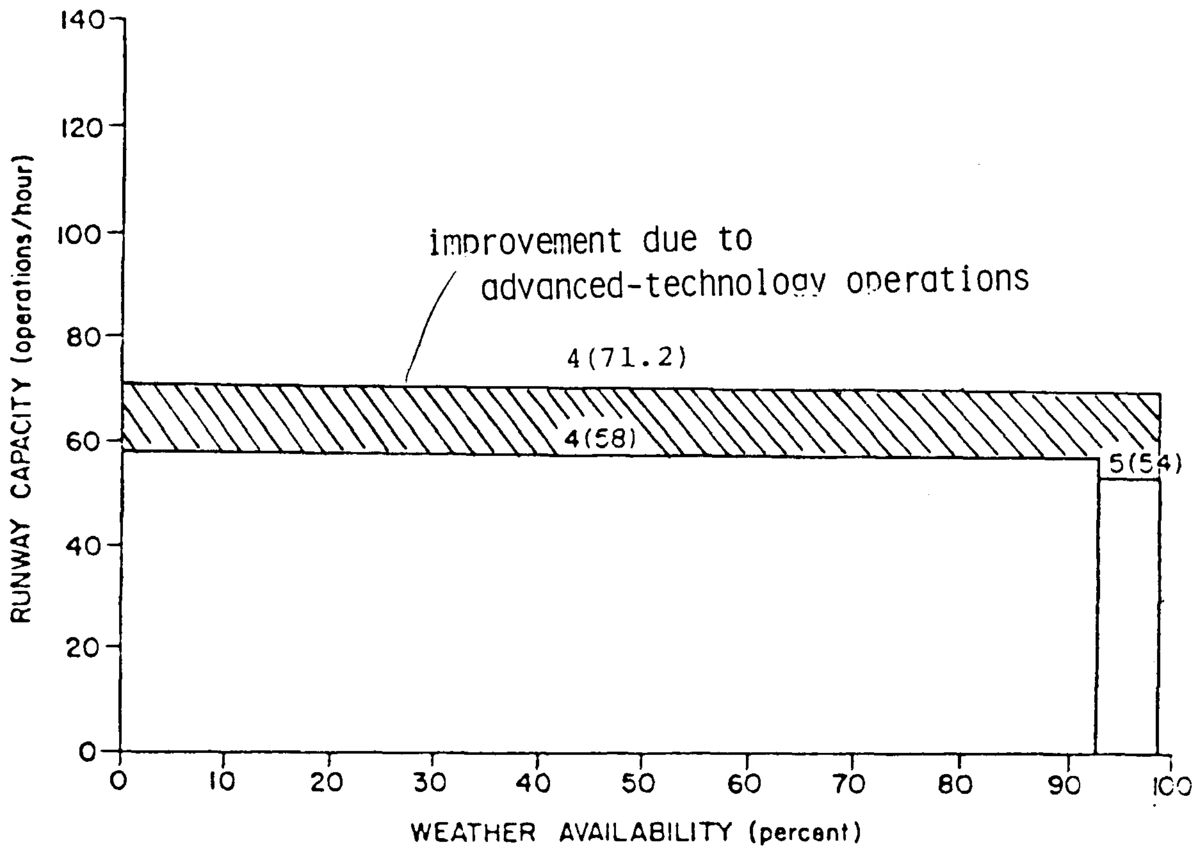


FIGURE 3.25. COVERAGE CHART WITH ADVANCED TECHNOLOGY: IFR-3 (0.81%) AT BOSTON LOGAN



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15. Supplementary Notes

Langley Technical Monitor: David A. Hinton

16. Abstract

Advanced technologies for airborne systems (automatic flight control, flight displays, navigation) and for ground ATC systems (digital communications, improved surveillance and tracking, automated decision-making) create the possibility of advanced ATC operations and procedures which can bring increased capacity for runway systems. A systematic analysis is carried out in this report to identify certain such advanced ATC operations, and then to evaluate the potential benefits accruing over time at typical US high-density airports (Denver and Boston). The study is divided into three parts: Part 1, "A Critical Examination of Factors Which Determine Operational Capacity of Runway Systems at Major Airports", is an intensive review of current US separation criteria and terminal area ATC operations. It identifies 11 new methods to increase the capacity of landings and takeoffs for runway systems; Part 2 - "Development of Risk Based Separation Criteria is the development of a rational structure for establishing reduced ATC separation criteria which meet a consistent Target Level of Safety using advanced technology and operational procedures; Part 3 - "Estimation of Capacity Benefits from Advanced Terminal Area Operations - Denver and Boston", provides an estimate of the overall annual improvement in runway capacity which might be expected at Denver and Boston from using some of the advanced ATC procedures developed in Part 1. Whereas Boston achieved a substantial 37% increase, Denver only achieved a 4.7% increase in its overall annual capacity.

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