DELAYED FLAP APPROACH PROCEDURES FOR NOISE ABATEMENT AND FUEL CONSERVATION

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SUMMARY

The objective of this program is to investigate the Delayed Flap Approach, which is an operational procedure designed to reduce fuel and noise in the landing approach of a jet transport. This report will describe the delayed flap operational procedures, discuss pilot acceptability of those procedures and displays, and show fuel/noise benefits resulting from flight tests and simulation.

INTRODUCTION

The conventional jet transport stabilized landing approach procedure requires moderately high thrust settings for an extended time, with the accompanying community noise impact and relatively high fuel consumption. Significant reductions in both noise generation and fuel consumption can be gained through careful tailoring of the approach flight path, the operational procedures, and the airspeed profile. For example, the noise problem has been attacked in recent years with development of the two-segment approach, which brings the aircraft in at a steeper angle initially and achieves noise reduction through lower thrust settings and high altitudes during most of the approach (refs. 1, 2).

Also, the Air Transport Association (ATA) member airlines have developed and instituted the "reduced flap" noise abatement landing procedures throughout most of the domestic airline systems (ref. 3). For this approach, the aircraft flies the standard straight-in path, but maintains a flap setting "one notch less" than minimum landing flap setting until final landing flap deployment at about 305 m (1000 ft) altitude. The final landing flap selected would be the minimum certified landing flap setting which is permissible for the particular landing. The intent is to assure that final approach stabilization is achieved at not less than 152 m (500 ft) above field elevation.

More recently, Lufthansa German airlines pioneered a low-drag/low-power approach technique (known as the TIPTOE approach) and has made it their standard ILS approach procedure (ref. 4). This technique is being considered for adoption by the International Air Transport Association (IATA) for use by all member airlines at landing fields where ground facilities permit. The target stabilization altitude for the IATA approach is 305 m (1000 ft) above field elevation. Both the ATA and IATA techniques comprise a decelerating process, employing delays and/or reductions in the extension of the landing gear and the use of flaps, with a consequent reduction in the amount of power required to conduct the approach. Both are "thumb-rule" techniques, where pilot action is keyed on aircraft velocity and altitude above the ground and DME information when available.

The NASA/Ames Research Center is currently investigating the so-called "delayed flap" approach (refs. 5-7) where pilot actions are determined and prescribed by an onboard digital computer. The onboard digital computer determines the proper timing for the deployment of the landing gear and flaps based on the existing winds and airplane gross weight. Advisory commands are displayed to the pilot. The approach is flown along the conventional ILS glide slope but is initiated at a higher airspeed and in a clean aircraft configuration that allows for low thrust and results in reduced noise and fuel consumption.

The procedure is an application of energy management concepts, where the proper timing of the deployment of the landing gear and flaps is used to dissipate the energy in a controlled manner while the engines are at low throttle setting.

This procedure has several advantages over the ATA and the Lufthansa types of approaches. The computation capability provides for consistency of operations and allows additional noise relief and fuel savings. The system has the potential for increasing operational safety by lessening pilot workload and providing an energy management engine-out landing capability and a wind shear detection and warning function. The primary disadvantage is, of course, the requirement for additional avionics. Definition of this equipment and associated costs are the subject of an ongoing study.

The elements of the Ames delayed flap program consist of operation with the NASA Convair 990 airplane (shown in fig. 1) and application of the concept to other aircraft.

The program has proceeded through an analysis and a piloted simulation phase and more than 100 hr of flight test evaluation onboard the CV-990.

The results of the flight test evaluation which show the fuel and noise benefits will be presented and discussed. The results of a limited guest pilot evaluation of the procedures will also be presented.

Ames has contracted with the Boeing Commercial Airplane Company to investigate the benefits and problems associated with the application of the delayed flap concepts to an aircraft in the current fleet. The results of the Boeing analysis of the fuel and noise benefits for the Boeing 727 airplane are complete and will be presented.

OPERATIONAL PROCEDURES AND DISPLAY CONCEPT

Figure 2 shows a typical delayed flap approach for the CV-990. In contrast to a conventional stabilized approach, which is flown at a constant airspeed of about 150 knots and moderately high thrust settings throughout the approach, the delayed flap approach begins at a higher initial airspeed, 240 knots and decelerates at idle thrust through most of the approach. The pilot intercepts the ILS glidepath at about 10 n. mi. from touchdown and at approximately 900 m altitude. He then retards the throttles to the idle detent and begins a slow deceleration. At about 6 n. mi. and 230 knots, the pilot is given a command from the digital computer to lower the landing gear. At about 5 n. mi. and 220 knots a command is given to lower approach flaps, and flaps are commanded to the landing position at about 4 n. mi. and 200 knots. The aircraft decelerates to final approach airspeed at about 150 m altitude, at which point the pilot advances the throttles to approach power and the last portion of the approach is flown at a stabilized airspeed similar to a conventional approach. In headwinds, extension of landing gear and flaps is delayed and in a tailwind condition, they are commanded farther out in the approach. Thus, regardless of wind conditions, the aircraft is always stabilized for landing at 150 m altitude, which is consistent with current airline procedures.

Figure 3 shows the CV-990 cockpit and displays that the pilot uses to perform a delayed flap approach. In addition to the normal instruments are a fast/slow indicator which is part of the ADI, an alphanumeric message display, and a data entry keyboard.

The fast/slow display, which is commonly found in many current jet transports, allows the pilot to monitor the energy state of the aircraft. While on the glide path, this instrument tells the pilot how the aircraft is decelerating relative to the desired airspeed schedule. This is similar to the way fast/slow displays are normally used, except that the usual reference airspeed is constant and not changed as in this case for a delayed flap approach.

The message display signals the pilot when to extend landing gear, approach and landing flaps, and when to apply approach power. The proper timing of signals is accomplished by a digital computer onboard the CV-990 aircraft. In essence, the computer predicts the manner in which the aircraft will decelerate during the approach to landing, taking into account the wind and changing aircraft weight. Based upon this computed deceleration, the computer signals the pilot when the flaps or gear is to be lowered by flashing a command on the message display. When the pilot has taken the required action, the display goes blank again until the next event is to occur. All this is accomplished so that the aircraft arrives at the final approach airspeed at precisely the right altitude and desired distance from touchdown.

The data entry keyboard provides a means for communicating with the digital computer. For a delayed flap approach, it would be used to input landing site data, such as the field elevation or ILS glide slope angle.

The equipment shown in figure 3 is not meant to represent an actual airline installation. The digital computer system and the CV-990[1] airplane were used in this program because of their availability and their ability to perform the required tasks. The avionics that could be installed in a conventional jet transport in order to have a delayed flap approach capability would be tailored to meet the requirements of the airlines.

RESULTS AND DISCUSSIONS

CV-990 Operations

Noise Measurement Results

A series of noise measurements was made during the flight test evaluation of the delayed flap approach in the NASA CV-990 aircraft at the Edwards Air Force Base (EAFB) test range. The purpose was to measure and compare the noise level on the ground under the flight path while using different types of operational procedures which included the conventional, the ATA reduced flap and the delayed flap approaches.

A total of 10 noise measurement sites was utilized. Six of the sites were located on the extended runway centerline from one to 6 n. mi. from the runway threshold. The remaining four sites were located at various sideline distances along the test range. These measurements were made with the assistance of Dryden Flight Research Center personnel during a flight test series in September 1975. The noise recording equipment and the ground radar tracking data were time correlated to provide the position of the aircraft relative to the sound measurement equipment during the tests.

The approaches were conducted during several days of flight testing under conditions where the low altitude winds varied from 1 to 16 knots and the aircraft weight varied from 59,000 kg (1[illegible],000 lb) to 64,000 kg (141,000 lb) on the different approaches. In addition, the elevation of the test site at EAFB was 696 m above mean sea level, and the ILS glide-slope angle was 2.5° which is lower than the typical 3° glide slope found at most airports. These factors complicate the analysis and interpretation of the data since they affect the geometry of the flight path, the sequence of operational procedures and the jet engine thrust levels during the approaches and thus, the noise and fuel measurements. In order to present a consistent set of data for direct comparisons between the different types of approaches, it was decided to use the inflight results primarily to validate existing aircraft aerodynamics, engine noise, and fuel usage [illegible]. By adjusting the parameters of the computer models to [illegible] the flight data, the resulting models could be used with confidence to generate data for direct comparison under identical test conditions. The details of the

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[1] The CV-990 aircraft is a four engine jet [illegible] of the DC-8, B-707 vintage. This aircraft is equipped with General Electric CJ-805-23B turbofan jet engines, trailing edge Fowler flaps and leading edge Krueger flaps.

computer analysis are given in reference 7. The subsequent figures present the results of this computer analysis.

Figure 4 shows the centerline noise level generated by the CV-990 aircraft on each of three types of approaches: the conventional, the ATA reduced flap and the delayed flap. These data are for the more typical 3° approach path. The approaches are all for a no-wind condition at an aircraft weight of 81,650 kg (180,000 lb). Plotted is the effective perceived noise level in dB (EPNLdB) versus the range to touchdown in nautical miles. Beyond glide-slope capture the aircraft in each case is flying at a constant 900 m altitude. Glide-slope capture occurs at about 9-1/2 n. mi. from touchdown.

The 150 m stabilization altitude for the delayed flap approach is indicated at about 2 n. mi. Inside of 2 n. mi. the aircraft configuration and thrust level are about the same for each approach and the noise levels are about equal. Between 8 n. mi. and 2 n. mi. there is a significant reduction in noise generated by the aircraft on a delayed flap approach. A 10- to 12-dB reduction is indicated over both the conventional and reduced flap approach.

The sideline noise data was also generated for each of the three approach types. These data were generated by the computer noise model, which used the flight test sideline noise measurements to refine the model parameters. The areas of the resulting contours were then calculated so that a direct comparison of the noise impacted areas could be made. The 90-EPNLdB contour areas for each of the three types of approaches are included in figure 5.

Figure 5 shows the CV-990 benefits comparison for the three different approach techniques: the conventional, reduced flap and delayed flap approach, in terms of the 90-EPNLdB noise contour area under each flight path (in km^2); the time expended on the approach (in minutes) from the common initial point at 15 n. mi. out, to touchdown; and the fuel consumed by the aircraft during each approach (in kg).

The current airline procedure (the reduced flap approach) has a contour area only 80 percent that of the conventional approach. Thus, the airlines have been able to achieve some noise reduction using operational procedures which do not require the additional [illegible].

The delayed flap procedure offers considerable additional noise relief. This contour area is only 1/4 as large as that for the conventional approach and less than 1/3 the size for that of the current airline procedure.

Fuel and Time Benefits

Presented in the upper set of bar charts is the fuel used during each of the three types of approaches.

A fuel measurement system was developed and installed in the CV-990 aircraft to sample and provide a continuous measurement of the fuel flow to each of the four engines. Fuel flow to each engine is summed in the digital computer to update the weight of the aircraft in real-time. A continuous record of the fuel use is therefore available throughout the flight mission. As mechanized, the system has a resolution of 3.6 kg (8 lb). It has been estimated that during the approximate 5-min duration of an approach the fuel used can be determined to within ±7 kg (±15 lb).

During the flight test onboard the CV-990, the fuel consumed was measured for a series of each of the different types of approaches (the conventional, ATA reduced flap, and the delayed flap). The same initial condition was established prior to beginning each approach. This initial condition was: range from touchdown 15 n. mi.; altitude approximately 900 m (3000 ft); indicated airspeed 240 knots; and flaps and landing gear up. The resulting flight data was again used to validate a computer model from which a directly comparable set of data could be generated for identical test condition. This data is shown in the bar charts of figure 5.

The current airline procedure (Reduced Flap Approach) saves 50 kg of fuel over the conventional approach, while the delayed flap approach saves an additional 130 kg over the reduced flap approach.

The delayed flap approach does require additional avionics, but the cost of this avionics could possibly be recovered in a reasonable period of time from the cost of fuel saved.

Time savings are also important to airline operations, and it is shown in figure 5 that the delayed flap approach saves a minute of operating time over both the reduced and conventional approaches.

Application to Current Airlines Aircraft

NASA has contracted with the Boeing Commercial Airplane Company to evaluate the delayed flap concept on an aircraft which is representative of those in current airline use. The objective is to examine some of the problems associated with the application of the delayed flap concept to a current aircraft and to evaluate the fuel and noise benefits. The operational flight procedures, computer algorithm and benefits will be different for each type of aircraft. Presented in this section will be a portion of the study results for the Boeing 727 airplane. Complete study results are presented in reference 8.

Boeing 727 Operational Procedure

Presented in figure 6 is an example of the delayed flap procedure as adapted to the Boeing 727 aircraft. The figure shows the altitude and airspeed profiles as a function of range to touchdown. The various events which occur during the approach are indicated on the airspeed profile. The aircraft provides five flap detents to control the energy during the approach. If the approach is initiated from 900 m and 220 knots, as shown here, idle thrust is commanded just prior to glide-slope capture. The commands are illuminated on an annunciator on the Pilots Panel of the B-727. As the approach progresses the command will be generated in the sequence shown in the figure (i.e., flap = 2°, 5°, 15°, etc.).

For non-icing conditions the deceleration is arrested by reapplying thrust in two steps, first to an engine pressure ratio (EPR) of 1.1 (at about 2.5 n. mi.) and then to normal approach power setting (about EPR 1.3) at the target altitude of 150 m. The first step to EPR 1.1 initiates engine acceleration to a power setting near the surge bleed valve operating point from which further acceleration can be obtained more rapidly when required. This is a characteristic of the particular engine in the B-727-200 airplane (i.e., JT8D-9). From 150 m through to landing, the aircraft is operated as on a conventional or stabilized approach. For an icing condition, the throttle setting would be maintained above idle at about 55 percent rpm for inlet anti-icing. An EPR of 1.2 is the minimum which would insure this thrust level. The flap and gear extensions will always occur in the same sequence but will not always occur at the same speeds. This will depend on the wind condition, the weight of the aircraft, and the initial conditions. For headwind conditions the sequence of procedures becomes more compressed, while in tailwinds the events will be strung out.

Weight variations have little effect on the deceleration distance or general shape of the airspeed-range curve. Increased weights generally shift the airspeed curve upward by an amount equal to the increase in V_{ref}. Thus, configuration changes occur at a higher airspeed.

The flap speed schedule shown on the figure is selected to minimize the pitch attitude changes during flap extension on the final approach. This is desirable for good glide-slope tracking by both the pilot and autopilot. It was shown in reference 8 that the current 727 autopilot controls these disturbances quite well. Fortunately, the minimum pitch disturbance schedule also provides adequate speed margins from safety limits, as represented by the stall speed region and flap placard boundaries, and is a good compromise with respect to fuel and noise benefits, which will be discussed next.

Noise, Fuel, and Time Benefits

The results of a benefits analysis for the B-727 aircraft are shown in figure 7. Computed fuel usage, elapsed time on the approach and noise [illegible] areas are compared for three different operational procedures in still air conditions. All approaches are initiated in a clean aircraft configuration at the same flight conditions. The data show that consistent benefits are realized for the B-727 when conducting a delayed flap approach as compared to either the conventional and reduced flap. For example, compared to the current airline procedure (reduced flap), a fuel saving of 1.0 kg is achieved, almost 1-1/2 min in time is saved, and a reduction in the noise area to 1/3 the size of that generated by the B-727 on a reduced flap approach is realized.

Although the data presented is for a no-wind condition, the relative benefit comparison for fuel, time and noise is not significantly different for headwind and tailwind conditions. The effects of a 30-knot headwind and a 10-knot tailwind are included in reference 8, in addition to the noise effects with acoustically treated nacelles.

Pilot Evaluation

In November 1975 nine guest pilots participated in an inflight evaluation of the delayed flap procedure and display concepts onboard the CV-990 airplane. These guests represented United and American Airlines, the Boeing, Douglas, and Lockheed companies, and the FAA, ALPA, and ATA organizations. The flight operations were conducted at the Sacramento Metropolitan Airport, Sacramento, California, under VFR conditions.

During this series of flight tests, each guest pilot conducted from three to six of the different types of approaches either as command pilot in the left-hand seat or as safety pilot/observer in the right-hand seat. The pilots acted upon the sequence of messages as they were displayed on the message display and manually deployed the landing gear and flaps, and operated the throttles. The approaches were primarily conducted in a coupled autopilot mode. Generally, the approach was stabilized in airspeed and aircraft configuration at 150 m altitude and continued through to touchdown. Comments and opinions were solicited from each guest pilot after the flights. A preliminary assessment of the operational procedures is summarized as follows.

Under the conditions of these tests most pilots indicated no significant increase in pilot workload for the delayed flap approach over the conventional approach, and felt that reversion to a conventional approach could be made safely and easily in the event of delayed-flap equipment malfunction. Consistent performance by the pilots and system was demonstrated in controlling the deceleration to achieve the reference velocity at 150 m altitude on the approach regardless of aircraft gross weight and existing wind conditions. The higher airspeeds existing during the approaches were not indicated as a problem by any of the guest pilots.

There were several comments made by the guests pointing out the potential difficulty of integrating the high-speed delayed flap procedure into the existing Air Traffic Control environment. It was indicated that this might be especially difficult at high density airports such as Chicago's O'Hare or Los Angeles International.

Generally, the guests were in agreement that the operational procedure and displays were acceptable and that the technique provided benefits for noise relief and fuel saving, but it was also the consensus that additional research would be required before the delayed flap technique could be considered an acceptable alternative for the current airline approach procedures.

CONCLUSIONS

Analytical, simulation, and inflight studies have been conducted to investigate the delayed flap approach technique. Inflight measurements of fuel usage and ground measurements of perceived noise were made during flight test with the NASA CV-990 airplane to assess potential benefits of the approach technique. Results show that significant benefits may be obtained using the delayed flap approach technique. Onboard the CV-990, guest pilots conducted a limited investigation of the acceptability of the operational procedures. A generally favorable response was obtained from these guests. Studies are underway to apply the delayed flap concepts to an example of a current airline aircraft. Application of the approach technique to the operation of a B-727-200 airplane shows that when compared to the reduced flap approach, significant savings in fuel, flight time and reduction in the noise impact area are achieved by using the delayed flap approach.

Several critical areas of research need study before the delayed flap approach could be considered an alternative to the present airline approach techniques. These areas include avionics retrofit costs, operational safety, and compatibility with the existing air traffic control environment.

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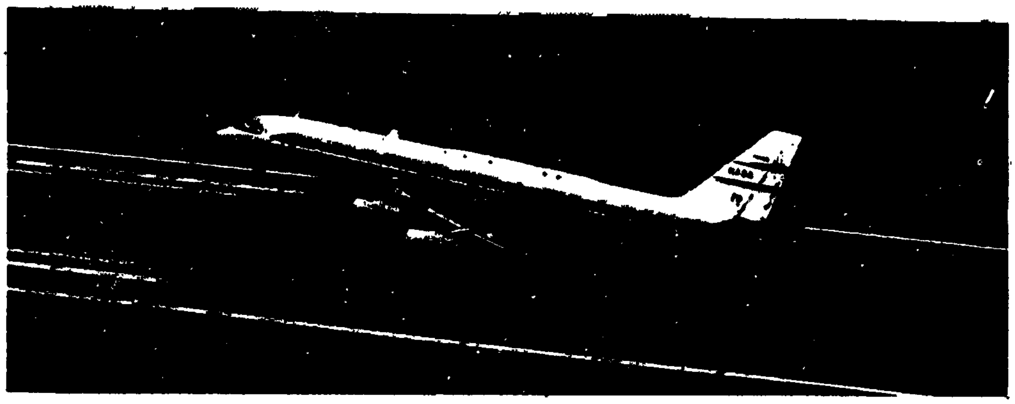

Figure 1.- CV-990 aircraft.

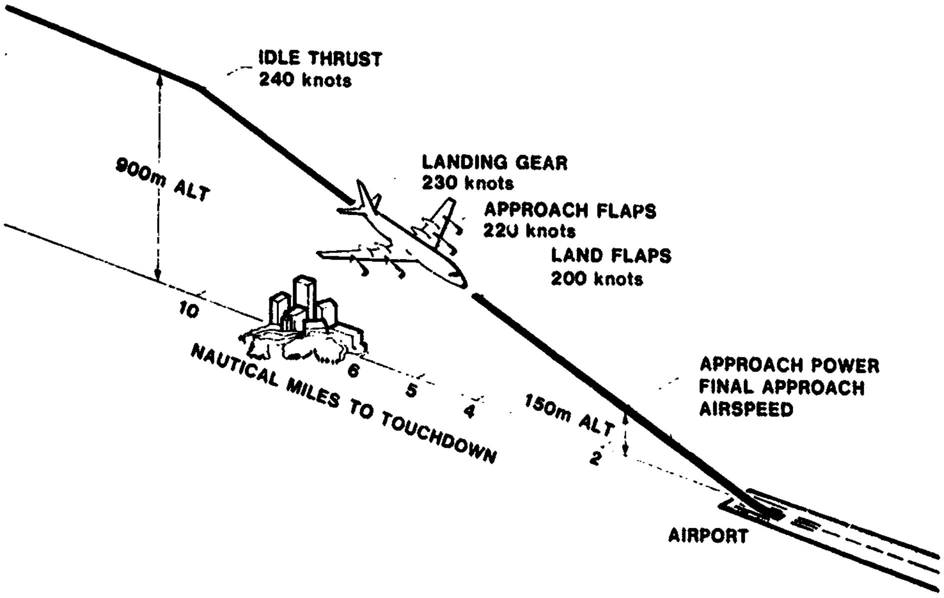

Figure 2.- CV-990 delayed flap approach profile.

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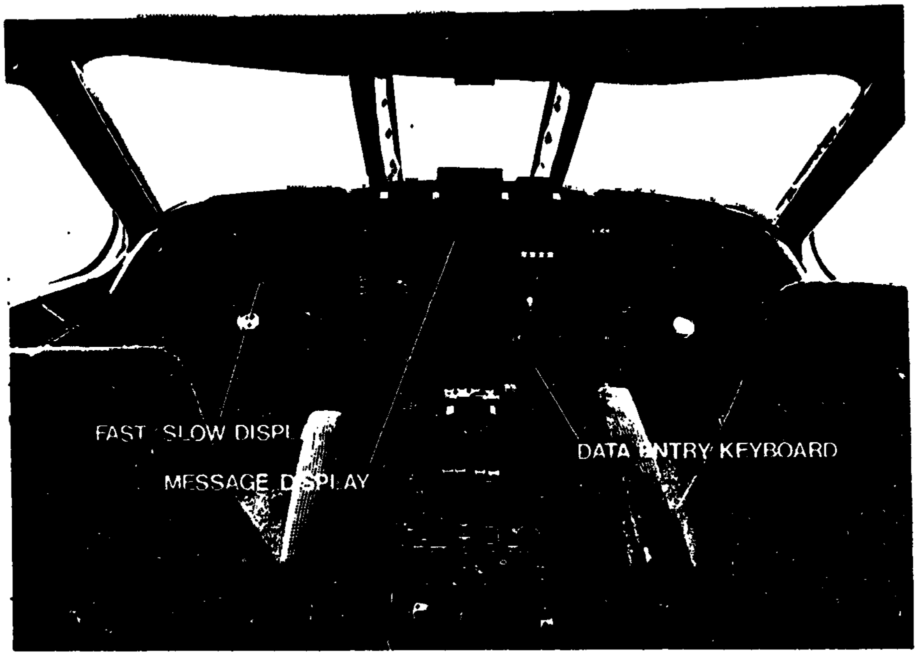

Figure 3.- CV-990 cockpit and displays used in delayed flap approach.

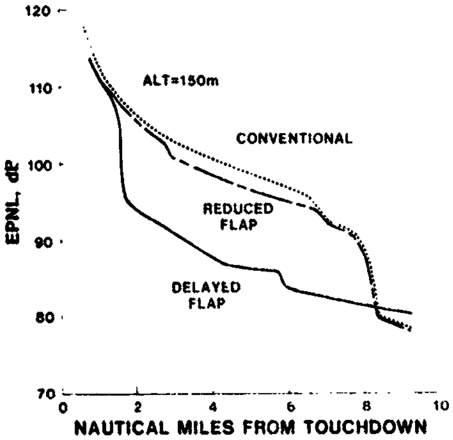

Figure 4.- CV-990 centerline noise comparison for 3° glidepath.

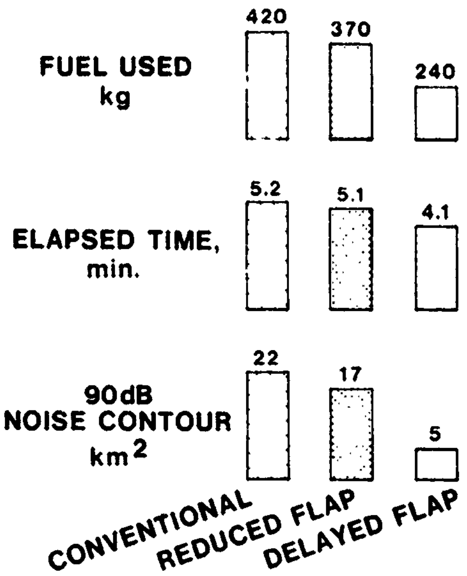

Figure 5.- CV-990 benefits comparison.

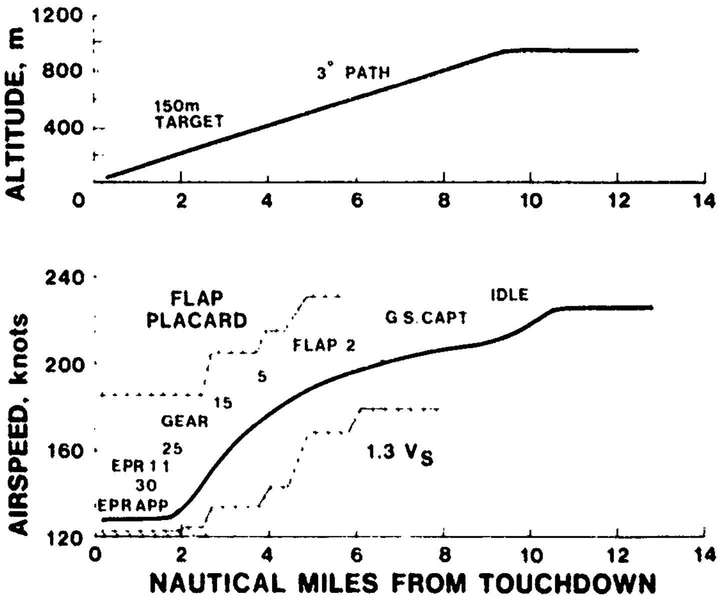

Figure 6.- Boeing 727 delayed flap approach profile.

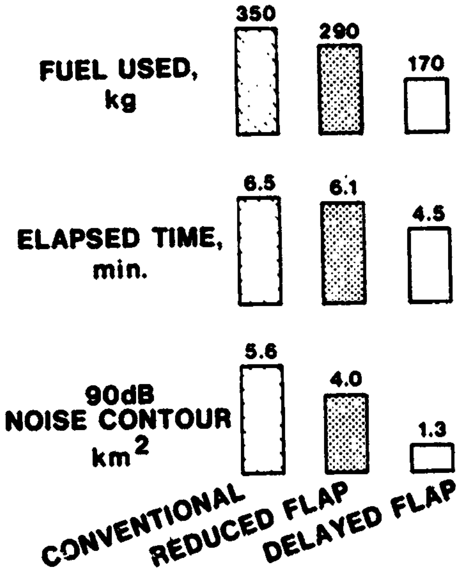

Figure 7.- B-727 benefits comparison.