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Signature Chris Barnett
Date August 1986

IN-FLIGHT INTELLIGENT PERFORMANCE MANAGEMENT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Chris Barret

August 1986

TO
A FRIEND
WHO DIRECTED MY LIFE
DR. WERNHER VON BRAUN

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ABSTRACT

This thesis investigates possible uses of a flight expert system (FLES) for in-flight performance management of commercial transport aircraft.

Advanced systems of 1995 commercial transports have been considered, together with the components and sensors of commercial transport internal systems. Conferences have been held with today's airline pilots to assess current and future flight deck needs in terms of FLES capability.

It has been determined that pilot workload could be alleviated by FLES functioning as a Performance Flight Engineer. Airline takeoff accidents could be significantly reduced by a FLES early detection and diagnosis of inadequate takeoff acceleration. Flight safety of impaired aircraft could be enhanced by a FLES assessment of performance penalties, and optimization of flight performance parameters.

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LIST OF SYMBOLS AND ABBREVIATIONS

Latin

a	Aircraft takeoff acceleration; Local speed of sound
AC	Alternating current
AFD	Aft flight deck
AI	Artificial Intelligence
AIM	Airman's Information Manual
AR	Aspect ratio
ATC	Air Traffic Control
ATIS	Airport Terminal Information Service
c	Specific fuel consumption, SFC
C_D	Coefficient of drag
C_{D_0}	Zero lift coefficient of drag
C_L	Coefficient of lift
cg	Center of gravity
CRT	Cathode Ray Tube
d	Runway contamination factor
D	Drag
DC	Direct current
e	Oswald's efficiency factor
E	Endurance
EGT	Exhaust Gas Temperature
EPR	Engine Pressure Ratio
F	Force

FF	Fuel flow
FFD	Forward flight deck
FLES	Flight expert system
ft	Feet
g	Gravitational acceleration
h	Altitude
hr/hrs	Hour/hours
INS	Inertial Navigation System
IWBS	Integral Weight and Balance System
K	$1 / [\pi e (AR)]$
K_1, K_2	Manufacturer constants
kts	Knots = nautical miles/hour (1 kt = 1.6878 ft/sec)
L	Lift
lb	Pounds
L.E.	Leading Edge
LISP	Primary artificial intelligence programming language
m	Mass
M	Mach number
MAC	Mean aerodynamic chord
MSL	Mean Sea Level
n	Number of engines
N_1	Low pressure compressor RPM
N_2	High pressure compressor RPM
NASA	National Aeronautics and Space Administration
q	Incompressible dynamic pressure

q_c	Compressible dynamic pressure
R	Range -- no wind
R_e	Radius of the earth ($R_e = 20,855,531.5$ ft)
R_w	Range with wind included
S	Projected area of the wing
SAS	Stability augmentation system
sec	Second
SFC	Specific fuel consumption, c
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
STOW	Systems for takeoff weight
t	Time
T	Thrust
TCV	Terminal configured vehicle
T.E.	Trailing Edge
V	Velocity; Volts
V_1	Critical takeoff decision speed
V_R	Rotational velocity
V_2	Velocity at height of 35 feet
V_w	Velocity of wind
W	Weight of aircraft
W_o	Initial weight
W_1	Final weight

Greek

α	Angle of attack
μ	Rolling coefficient of friction
π	Constant for the quadrature of the circle ($\pi = 3.1415927$)
ρ	Atmospheric density
θ	Runway slope in radians

CHAPTER I

INTRODUCTION

According to the research study done by the Lockheed-Georgia Company, the 1995 commercial transport aircraft will be a more complex vehicle employing much advanced technology, and yet be flown by only two pilots.⁶⁹ In addition, current three-pilot aircraft, such as the Boeing 747, are being reduced to two-pilot aircraft.⁴⁸ Since future commercial transports will operate with more systems to manage and fewer human pilots, advanced in-flight performance management systems will be required.

One example of advanced technology on the 1995 transport is active control systems using all-electric flight controls.⁹ The 1995 transport will have no hydraulic systems. The flight controls will be operated by all-electric actuators.⁶⁹ Active control systems allow reduced aircraft structural weight, however they also can increase the chances of control surface malfunctions. Control surface malfunctions can be increased because more control surfaces will be used, and because the control surfaces will be used in both conventional and non-conventional configurations. On the wing alone there will be 38 control surfaces on the 1995 transport.^{69,9} For the details of these control surfaces and their operation see Appendix A. In the event of a control surface malfunction

the aircraft performance may suffer.

An advanced in-flight performance management system should be able to accommodate control surface malfunctions. The malfunctions should be detected instantly and displayed to the crew on a CRT. This would allow the Captain to quickly correct any flight asymmetries. The performance penalties should then be assessed, and the flight performance parameters of the impaired aircraft should be optimized.

A flight expert system (FLES) is being developed at the University of Tennessee Space Institute through the efforts of the Computer Science Department and the Flight Research Department.^{3,4} The research is being sponsored by the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) Langley Research Center. FLES has the capability to monitor components of aircraft systems and to diagnose malfunctions. FLES uses domain knowledge to perform fault diagnosis. Domain knowledge is represented in a network of frames, rather than if-then rules. FLES uses three types of frames: sensor, malfunction, and maladjustment. The programming language is Lisp. FLES has been implemented on a Symbolics Lisp computer using the Lisp dialect Zetalisp.

This thesis investigates possible uses of FLES for in-flight performance management of transport aircraft. One important airline pilot need addressed in this thesis is takeoff performance management. All too often the engineer

designs aircraft systems without enough interaction with the pilots who will be the users of the system. This investigation has included conferences with today's airline pilots for their views on current and future flight deck needs. The NASA Langley Terminal Configured Vehicle (TCV) has been used in the example calculations. This research aircraft has been chosen because it has been modified to incorporate many 1995 transport concepts, and because it is used to evaluate new flight management systems for transport aircraft.^{54,83,84} For an overview of this aircraft see Appendix B. In view of 1995 transport advanced technologies and airline pilot needs, this thesis outlines some possible uses of FLES to reduce pilot workload and enhance flight safety by in-flight intelligent performance management.

CHAPTER II

TAKEOFF PERFORMANCE MANAGEMENT

This research has included conferences with airline pilots from Republic Airlines, Trans World Airways (TWA), Piedmont, and Braniff Airlines for their views on current and future flight deck needs.^{87,88,89} It was found that airline pilot needs were somewhat subjective. For example, pilots of northern routes were more concerned with improved automatic ice detection systems than pilots of southern routes. Many pilot needs were dependent upon the pilot's personal experience with malfunctions, incidents, or accidents. One of the airline Captains consulted had ten years of accident investigation experience with the National Transportation Safety Board (NTSB) in addition to his personal airline flying experience.⁸⁸ The causes of the accidents investigated contributed to his opinion of flight deck needs within FLES capability. However, all agreed that with a two-pilot flight deck FLES could reduce pilot workload by functioning as a Performance Flight Engineer, and flight safety could be enhanced by using FLES to detect and diagnose inadequate takeoff acceleration. An integral weight and balance system (IWBS) was identified by all as an important need. But the airline Captains unanimously agreed that one of the most important things FLES could do to improve flight safety was to detect and diagnose

inadequate takeoff acceleration.

2.1 PERFORMANCE FLIGHT ENGINEER

Since future transports will be flown by only two pilots, FLES could use its monitoring and diagnostic capability to reduce pilot workload by functioning as a Performance Flight Engineer. FLES could be responsible for the nearly 1,000 critical components of the aircraft performance information systems shown in Table 1. Instead of the pilots monitoring multiple arrays of dials and gauges, they would only monitor three CRT displays (see Appendix A and B). In addition, FLES would need data from all the aircraft systems which contained performance information in order to make performance assessments.

The sensors in these systems, which normally provide information to the instruments, could provide performance information directly to FLES. Components of aircraft systems use sensor redundancy to guard against sensor failure. The sensors vote before the information is sent to the corresponding instrument. This feature has been designed by aircraft instrumentation engineers to increase instrumentation reliability. Table 2 shows some typical sensor redundancies in the performance information systems.

FLES could use sensor information to guard operating ranges and issue alerts on the pilots' CRTs when a monitored parameter goes out of range.

Table 1. Aircraft Performance Information Systems

Flight Control Surfaces and Landing Gear:

Ailerons, Aileron Trim, Elevator, Elevator Trim, Rudder, Rudder Trim, Flaps, Slats, Spoilers, Winglets, Gear.

Main Engines:

Throttle Settings, EPR, EGT, N_1 , N_2 , FF, Fuel Quantity, Fuel Temperature, Oil Pressure, Oil Temperature, Oil Quantity, Inlet Vibration, Turbine Vibration, Fuel Pressure.

Avionics:

Flight Instruments, Autopilot, Radar, Navigation Computer. (Included with Flight Instruments are the Alerting Systems such as: Stall Warning, Collision Avoidance, Ground Proximity, and Wind-Shear Warning recently developed by Airbus Industries and Sperry.)

Pneumatics:

Pressurization System, Pitot-Static System, De-Icing System, Oxygen System.

Table 2. Typical Sensor Redundancy in
Performance Information Systems

Parameter	Number of Sensors ⁸
α (Angle of Attack)	2
Airspeed	20
EPR (Engine Pressure Ratio)	4
EGT (Exhaust Gas Temperature)	7
FF (Fuel Flow)	4
Landing Gear Position	3
Flap Position	8
Oil Temperature	2
Oil Pressure	4
N ₂ (High Pressure Compressor RPM)	2

FLES could use component relationships, time histories, and rapid rates of change to diagnose malfunctions and issue alerts of impending malfunctions. Thus, some problems could be prevented before they occurred.

The Performance Flight Engineer function of FLES would significantly reduce pilot workload by replacing the monitoring of many instruments with the monitoring of only FLES alerts on three CRTs. However, pilot requested values would take longer to "call up" than a glance at an instrument. Having the flight instrument information (outside air

temperature, pressure altitude, flap setting, wind velocity, aircraft weight, etc.) FLES could automatically present on a CRT all values the pilot normally has to look up in a manual, such as takeoff EPR, N_1 , stabilizer trim setting, and critical velocities.

FLES could be used to handle takeoff performance problems where data needed to be rapidly revised due to a minor malfunction. For example, in the event of an Antiskid System failure more runway is required, since an abort may require more stopping distance. Therefore, the limits of the takeoff maximum gross weight and first critical speed, V_1 , must be reduced.^{11,12} These reductions are a function of flap settings and runway length, which FLES would have from the flap position sensors and the navigation computer (see Appendix B) respectively. FLES could check the weight reduction first, and if not met advise the crew to abort the takeoff. If the weight reduction is met, FLES could then present the revised V_1 for the impaired takeoff.

For example, if the TCV aircraft was rolling at its maximum takeoff gross weight of 97,800 lb. and corresponding V_1 of 132 kts. when the Antiskid System failed, FLES could utilize its performance information to advise an abort since the weight is not 8,000 lb. below maximum gross as required for the TCV. On the other hand, if the TCV was rolling at a weight of 89,000 lb. and corresponding V_1 of 123 kts. when the Antiskid System failed, FLES could approve the weight

and go on to determine the revised V_1 of 104 kts. for the impaired takeoff. Thus, the Performance Flight Engineer function of FLES could be used to do much more than simply monitor, and would significantly reduce pilot workload.

2.2 THE NEED FOR DETECTION OF INADEQUATE TAKEOFF ACCELERATION

One of the most important needs of the airline pilots, that FLES could address, is the automatic detection and diagnosis of inadequate takeoff acceleration. Obtaining the necessary acceleration during the takeoff ground roll is very critical. However, today's airline pilots have no flight deck instrumentation to indicate the aircraft's takeoff acceleration. One reason the instrumentation is not provided is that the pilot workload would be increased if the pilot had to monitor the acceleration, along with the critical takeoff velocities, runway heading, instrument scan, and perform other duties during the few seconds of the takeoff ground roll.

The first critical takeoff velocity of significance to the airline pilot is V_1 , the decision speed.²⁶ V_1 provides a basic reference for a piloting decision as to whether to abandon or continue the takeoff. For example, if an engine fails before V_1 is reached, the takeoff is aborted. If an engine fails after V_1 , the takeoff is continued according to airline policy.^{11,12} The Balanced

Field Length is the minimum takeoff distance. The field (runway) is balanced when the distance to accelerate to V_1 with all engines operating, and then continue the takeoff with one engine inoperable is equal to the distance to accelerate to V_1 with all engines operating, and then come to a complete stop.^{26,10,13,77} The Balanced Field Length concept of assuming an engine failure as the most frequent cause of aborting a takeoff dates from reciprocating engine transports.³⁸ Since turbine engines are much more reliable than reciprocating engines, more takeoffs are aborted for other reasons and inadequate acceleration is not just engine related.

If for any reason, the takeoff acceleration is less than required, the aircraft will use more runway to reach V_1 than figured in the Balanced Field Length minimum takeoff distance. Hence, the distance remaining may not be enough for stopping the aircraft in the event of an abort, or in the case of a continued takeoff the safety margin may be compromised such that the aircraft may not clear obstacles at the end of the runway. Therefore, an inadequate takeoff acceleration must be detected early in the takeoff ground roll, so that the problem can be rectified, or the takeoff can be aborted at lower speeds with sufficient runway to stop.

Although airline pilots rely on engine instruments to determine whether thrust is adequate, they have little indication of increased resistance, such as that due to

parking brakes engaged, or airframe ice accumulation, which could seriously jeopardize the takeoff.⁶ There have been an alarming number of airline accidents attributed to inadequate takeoff acceleration, which have been investigated by the NTSB, a few of which are cited here.

In the recent death of 248 U.S. servicemen in Newfoundland the DC-8 took longer getting off the ground than normal.⁵² With early detection of inadequate acceleration this flight may have been safely aborted.

In an Air Florida accident (78 persons killed, Washington National Airport) flight deck recordings revealed that the First Officer said "That doesn't seem right, does it?" But, before the crew could identify the problem, the aircraft had crashed into the 14th Street Bridge and the Potomac River. The B-737 took 5,400 ft. of runway instead of 3,500 ft., and 45 seconds instead of 30 seconds, before liftoff.³⁸ The investigation revealed that an ice-blocked engine sensor resulted in inaccurate engine instrumentation. Takeoff performance was further deteriorated by airframe ice. The crew failed to perceive that the acceleration was inadequate and did not abort.¹⁹

In a Capitol International Airways accident (47 of 229 on board killed, Anchorage, Alaska) the DC-8 failed to accelerate to liftoff speed and ran off the end of the runway. The rotation speed, V_R , of 153.5 kts. should have

been reached in 5,700 ft. The maximum speed attained, 152 kts., was not reached until 10,400 ft. along the 10,900 ft. runway. The Captain later said "the acceleration felt normal up to 135 knots." However, at that speed the aircraft had already used 67 % more runway than normal, and had taken 50 % longer than normal. The investigation revealed that the parking brake was on during the takeoff.^{19,38}

Other reasons for inadequate takeoff acceleration, revealed by NTSB takeoff accident investigations, include: improper control surface configurations; engine power loss; tire failure; contaminated runways; improper takeoff performance calculations; and wind shear.¹⁹ If the inadequate acceleration had been detected early in the takeoff ground roll, many of these flights could have been safely aborted. The NTSB believes that serious accidents could be significantly reduced by takeoff acceleration monitoring systems.¹⁹

2.3 FLES DETECTION AND DIAGNOSIS OF INADEQUATE TAKEOFF

ACCELERATION

Flight safety could be greatly enhanced by FLES management of takeoff performance. During the takeoff, FLES could detect and diagnose inadequate acceleration by continuously comparing the actual acceleration with the required acceleration. As long as they were within limits, the pilots would

not be bothered with any information, and would not be required to monitor anything. If the acceleration was below normal, FLES would diagnose the cause and display a concise flashing warning message on the primary CRT. For example, if the brakes were the cause of the inadequate acceleration, an appropriate FLES response would be " ACC ↓ ; BRAKES " flashing on the primary CRT. This would arrest the attention of the crew and convey instantly that the acceleration was below normal because the brakes were on.

Since FLES can monitor in microseconds if necessary, it can far surpass human detection capabilities. FLES could detect and diagnose inadequate acceleration in the first few seconds of the takeoff roll. Thus, the Captain would have the opportunity to correct the problem, or to abort at low speeds with ample stopping distance.

The actual acceleration of the aircraft can be provided electronically to FLES through the sensors of any one of a number of acceleration measuring devices. These include separate accelerometers, the inertial navigation system (INS), and recently developed devices.^{6,19,38,52,56} One developed device is that of Frederick J. Bailey, Jr. This is a patented "Airplane Take-off Performance Indicator" which measures longitudinal acceleration.⁶ Another recently developed device is that of Dr.'s Mancil Milligan and Joe Wilkerson of the University of Tennessee called a takeoff performance indicator.⁵² One B-747 pilot, Captain George

Terhune, of Pan American World Airways has outlined how the actual aircraft acceleration can be provided by the INS.¹⁹ The British Civil Aviation Authority has also developed devices, since its stipulation that the rate of fatal takeoff accidents on commercial aircraft must be reduced.³² As mentioned in the previous section and seen in Table 2, multiple sensors are used to guard against sensor failure and increase reliability. Sensor redundancy can be used for the acceleration sensors which would then vote before sending their information directly to FLES.

In order to manage the takeoff performance FLES would continuously compare the actual acceleration with the required acceleration, which could be provided by manufacturer's tables for the specific flight conditions. FLES could use a table look-up routine to obtain values of required acceleration for each corresponding value of time. For the TCV aircraft and the following conditions,

W	=	97,800 lb.
h	=	MSL
θ	=	0
Flaps	=	15°
Temperature	=	15° C

V_1 = 132 kts. and is to be reached in 29 seconds after brake release, at which time the aircraft is to be 1207 ft. down the runway. Since FLES can monitor in microseconds, if

the acceleration was below normal, FLES could detect and diagnose the problem in the first few seconds of the takeoff roll. This would allow the crew time to take action long before V_1 was reached. Thus, many of the above takeoff accidents could be prevented by low speed aborts and ample stopping distance, or ample takeoff clearance safety margins.

In the future, it may be possible to have FLES determine the required acceleration by performing on-board instantaneous calculations. FLES could use an acceleration formula algorithm derived from the takeoff ground roll equation of motion. This expression and the current problems associated with using it are discussed below.

To derive an expression for the required acceleration, Newton's second law is applied to the forces on the aircraft during the takeoff ground roll (see Figure 1). Summing forces,

$$T - D - W \sin \theta - \mu (W \cos \theta - L) = \frac{W}{g} a . \quad (1)$$

Since

$$L = C_L 1/2 \rho v^2 S \quad \text{and} \quad D = C_D 1/2 \rho v^2 S, \quad (2)$$

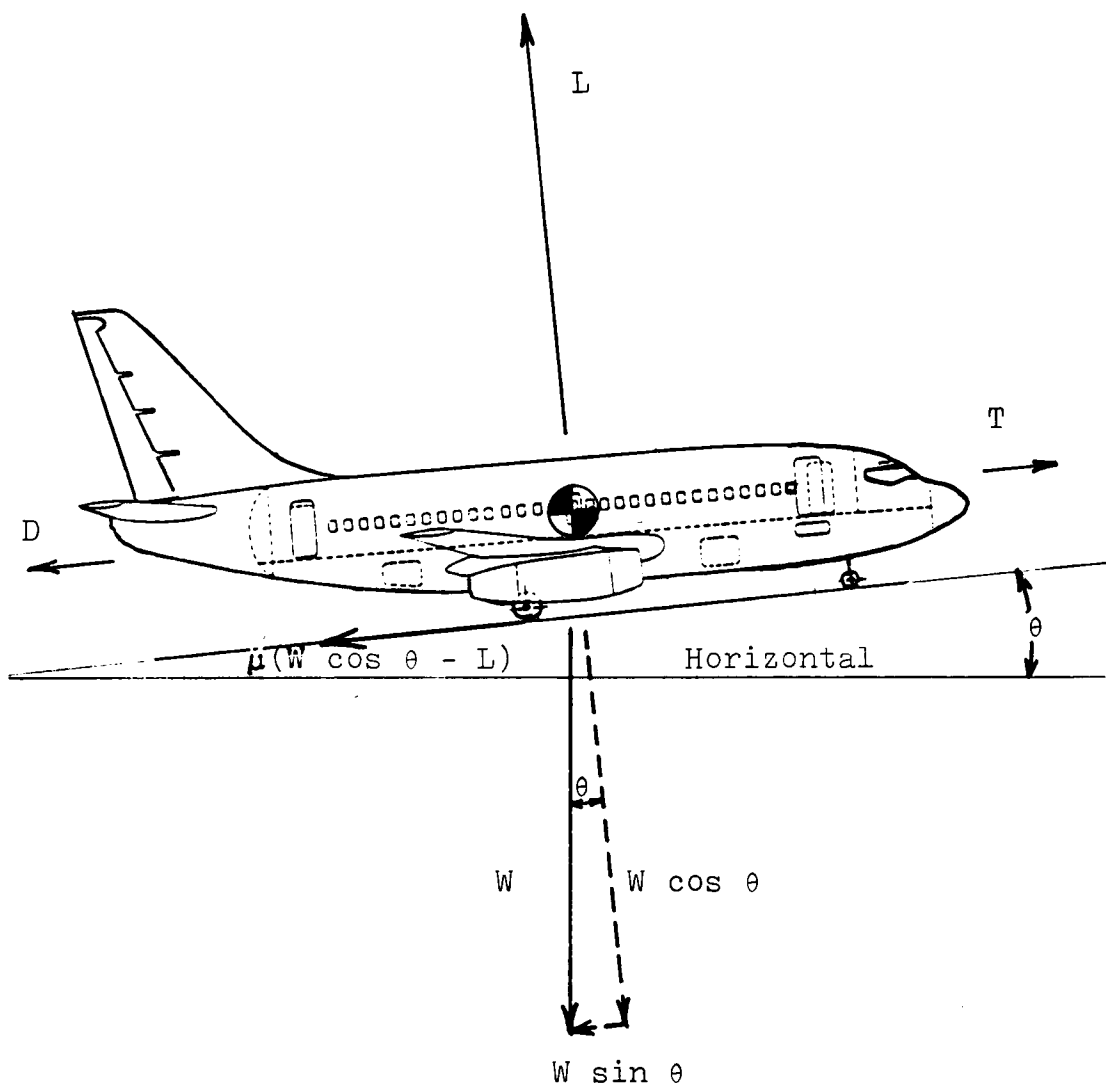


Figure 1. Forces on the TCV Aircraft During the Takeoff Roll

Equation (1) becomes:

$$a = g \left[\frac{T}{W} - \mu \cos \theta - (C_D - \mu C_L) \frac{\rho v^2 S}{2 W} - \sin \theta \right] . \quad (3)$$

The ten instantaneous parameters that FLES would need to use this formula are:

S, g, ρ , θ , V, μ , C_L , C_D , T, W.

The reference area of the aircraft wing, S, is a known constant which can be inserted into the FLES algorithm.

The gravitational acceleration, g, is a function of altitude above mean sea level (MSL).

$$g = 32.1741 \left(\frac{R_e}{R_e + h} \right)^2 ; \quad (4)$$

where R_e = radius of the earth = 20,855,531.5 feet.

For example, while

$$g \text{ at sea level} = 32.1741 \text{ ft/sec}^2,$$

$$g \text{ at 60,000 ft} = 31.9898 \text{ ft/sec}^2,$$

which is a change of .57 %. However, for the purpose of calculating the required takeoff acceleration, a constant value of the gravitational acceleration, g, can be used.

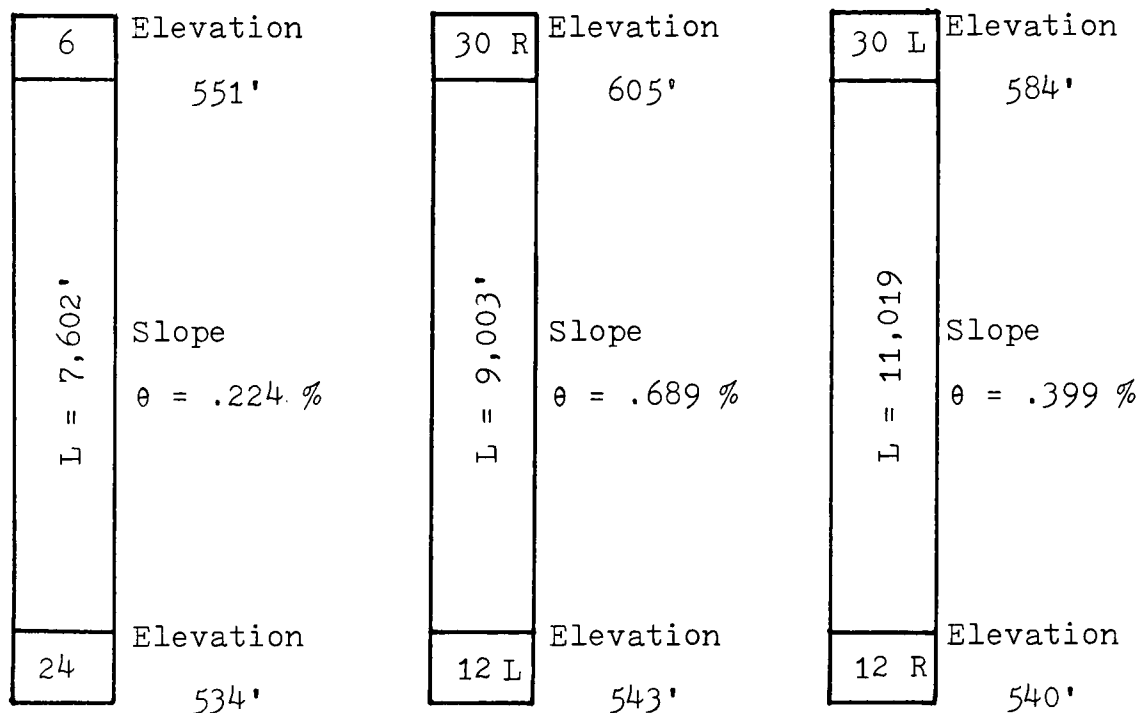
The atmospheric density, ρ , is a function of altitude and temperature. The FLES algorithm could obtain ρ from

pressure altitude information from the performance information systems.

The runway slope, θ , is known airport information given in percent upward or downward slope to two-digit accuracy. FLES could obtain θ from the navigational computer (see Appendix B) which provides θ on the TCV and on the 1995 transport. It is pointed out that the given runway slopes are sometimes average values of portions of upgrades and portions of downgrades in a runway. See Figure 2. The effect of a small error in θ would be negligible in the $\cos \theta$ term (θ in radians) in Equation (3), since runway slopes are well below 10 %. In the $\sin \theta$ term in Equation (3), a sizable error in θ could affect the result (e.g., 1 % error in $\theta \rightarrow \approx 7$ % error in a). This is not a limitation of FLES, but rather a limitation of available instantaneous runway slope detection equipment. With the development of an instantaneous runway slope sensor, the possible errors introduced here could be alleviated. It should be mentioned that while there is curvature in some runways, as depicted in Figure 2, and the average slopes that are given may not be linear, FLES would only require the slope values for the first few hundred feet of the end of the runway to perform its detection and diagnosis.

The velocity, V , can be provided directly to FLES from the pitot-static system (see Section 2.1).

Example Runways in St. Louis (Source - AIM):



Example Runways in Atlanta (Source - AIM):

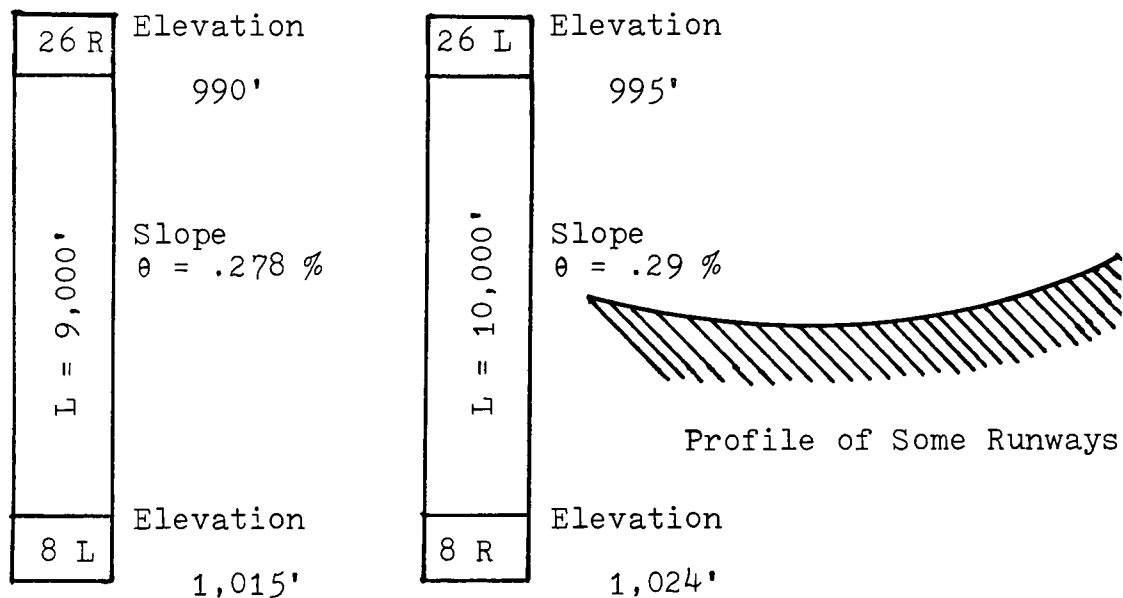


Figure 2. Example Runway Slopes (Atlanta and St. Louis)

The rolling coefficient of friction, μ , could be approximated by accepted standard values tabulated for runway surface conditions (e.g., $.02 + .02 d$ for hard concrete, where d = contamination factor depending on depth of slush). Since the average required acceleration of an airliner ($\approx .3g$) is much larger than μ , a small error in μ can be tolerated as shown below. From Equation (3),

$$a = g \left[\frac{T}{W} - \mu \cos \theta - (C_D - \mu C_L) \frac{\rho v^2 S}{2 W} - \sin \theta \right]$$

For the TCV at the above conditions, at

$$t = 5 \text{ sec}, \quad a = .254 g \quad \text{and}$$

$$.254 g = .2742 - \mu (.9789) \quad (5)$$

Equation (5) shows that a 15 % error in μ will result in only a .9 % error in the required acceleration.

The aerodynamic coefficients, C_L and C_D , are a function of flap setting and α , for low speeds. Most airliners use a parabolic drag polar and C_D becomes a function of C_L i.e.,

$$C_D = C_{D_0} + K C_L^2 \quad (6)$$

$$\text{where } K = 1/(\pi e AR) .$$

K and C_{D_0} are known constants for the aircraft. FLES could use the flap setting and α information provided by

the sensors (see Section 2.1) to retrieve C_L values from a table look-up. FLES could use an n-dimensional look-up and interpolation, or an m-order polynomial for C_L , C_D , and T values.

The instantaneous values of thrust, T , could be calculated by FLES using a manufacturer's empirical relation that is a function of static takeoff thrust and velocity. For example,

$$T = n (T_{\text{takeoff}} - K_1 V + K_2 V^2) \quad (7)$$

where T is in lb and V is in ft/sec

n = number of engines

K_1 , and K_2 are manufacturer's constants

There are also alternative means of determining the instantaneous on-board thrust values by recently devised direct measurement methods.^{29,63,85} (Also see Hosman, and Kleingeld.) However, accurate measurement of thrust from current on-board instrumentation is difficult.

The aircraft weight, W , is one of the greatest concerns in either a calculation, or a look-up of required acceleration. Many of our airliners today still use the obsolete method of approximating the Load Manifest. That is, an "average passenger" weight and an "average baggage" weight are used. Errors in aircraft weight of over 10,000 lb. are not uncommon.^{35,87,88} This problem can easily be

corrected using an integral weight and balance system, which could provide very accurate aircraft instantaneous weight directly to FLES. An integral weight and balance system (IWBS) could not only provide the weight accuracy required for FLES acceleration determination, but also the center of gravity (cg) accuracy required for many other performance calculations. Because future transports will use active control systems (see Appendix A) which require precise determination of weight and cg, many on-board IWBS's have been developed. These systems use a variety of methods ranging from inclinometers to strain gauges and pressure gauges.^{34,35,36,61} The weight and expense of the installation is well justified for the takeoff performance management alone.^{87,88,89}

To demonstrate the sensitivity of the required takeoff acceleration to weight, for the TCV at MSL and $t = 2$ sec and

$$S = 980 \text{ ft}^2$$

$$\theta = 0$$

$$\rho = .0023769 \text{ lb-sec}^2/\text{ft}^4$$

$$V = 10.10 \text{ kts.} = 17.06 \text{ ft/sec}$$

$$\mu = .02$$

$$C_L = 1.0$$

$$C_D = .03$$

$$T = 2 (14,000 - 14 V + .014 V^2) = 27,550 \text{ lb.}$$

$$W = 97,800 \text{ lb.}$$

the required acceleration is

$$a_{\text{required}} = .261 \text{ g.}$$

Suppose the takeoff weight was in error + 10,000 lb. i.e.,

W = 107,800 lb., then Equation (3) would give

$$a_{\text{required}} = .236 \text{ g.}$$

If the takeoff weight was in error - 10,000 lb. i.e.,

W = 87,800 lb., then Equation (3) would give

$$a_{\text{required}} = .294 \text{ g.}$$

Thus,

Takeoff weight error of + 10,000 lb. → a error of - 10 %.

Takeoff weight error of - 10,000 lb. → a error of + 13 %.

Therefore, an IWBS is a requirement for the success of accurate takeoff performance management.

If the actual and the required values were very close, FLES could use the actual acceleration value as the input to Equation (3) to produce an updated value of μ . The updated μ value could improve the acceleration calculations of the line of airliners behind waiting to take off. It is not within the scope of this investigation to detail methods for transferring FLES generated data from

aircraft to aircraft, but certainly the Airport Terminal Information Service (ATIS) is a possibility. An updated value of μ could also prove useful if the aircraft should have to takeoff again soon from the same runway, or if the aircraft should land on the same runway with a complete failure of all braking action. In that event, the acceleration algorithm could become the deceleration algorithm (thrust replaced by reverse thrust). FLES could display on a CRT the exact roll-out distance for the impaired aircraft. That is, it would be known far in advance whether the aircraft would roll off the runway, and if so how far off. Admittedly, these are unlikely events, however once FLES has been installed, it would cost nothing extra to update and store μ for the duration of a flight.

In summary, with the development of more accurate on-board instantaneous thrust and runway slope measuring devices, Equation (3) would be more practical for FLES to use. Until then, because of the errors that may be introduced by using current on-board thrust measurement and average runway slope values, a table look-up of predetermined required acceleration values may be preferable to the FLES instantaneous calculation.

When FLES compares the actual and the required values of the takeoff acceleration, if they are not within prescribed limits (e.g., 15 %), FLES could alert the crew with a warning and a diagnosis long before V_1 . The function

of FLES would not be to command an abort, but rather to provide vital information, thereby assisting the Captain in making critical decisions more efficiently, and much sooner in the takeoff ground roll. In diagnosing the cause of inadequate acceleration, FLES could search through selected component groups. Then FLES could use its knowledge of component relationships to search for a conformation or a conflict. FLES could also accommodate multiple malfunctions and prioritize multiple malfunctions in order of importance to the crew. FLES could do this at very high speeds, which would certainly out perform the human pilot. Therefore, FLES could be more thorough and check even unlikely faults that the pilot may not have the time to consider.

One selected component group that FLES could check is the deceleration group: brakes; automatic braking system; parking brakes; anti-skid system; and reverse thrust. Although highly unlikely, a clamshell door on a multi-engine aircraft could be partially deflected cancelling the forward thrust on one engine. Another group that FLES could check is the engine group: throttle setting; EPR; EGT; N_1 ; N_2 ; FF; fuel quantity; fuel temperature; fuel pressure; oil pressure; oil temperature; oil quantity; inlet vibration; and turbine vibration. An engine could be running but not producing enough forward thrust due to an improper setting, or an internal malfunction such as improper fuel flow or compressor rpm. In the pneumatics group FLES could check:

ice detection systems; and anti-ice systems. In the flight control group FLES could check: flap positions; spoiler positions; slat positions; primary flight control positions; and the takeoff trim setting. Deployed ground spoilers are normally automatically retracted when the throttles are advanced, if one has not retracted, or if any other control surface is out of position, this could cause the extra drag which would result in inadequate acceleration. FLES could also be used to check additional things such as tire pressures and proper sealing of cargo doors. In many cases the FLES diagnosis could save the takeoff by having the crew correct the problem in the first few seconds of the ground roll. In the event the problem cannot be corrected, or FLES cannot determine the problem, the FLES detection and warning would allow the Captain to abort the takeoff early in the takeoff ground roll.

Summarizing the takeoff performance management, since future transports will be flown with only two pilots, FLES could assist as a Performance Flight Engineer. FLES could be used to issue warnings to the crew on their CRTs when monitored parameters went out of range, and use its diagnostic and predicting capabilities to enhance flight safety. Having continuous information from the performance information systems on-board, along with tables stored in memory, FLES could manage the takeoff performance by detecting and diagnosing inadequate takeoff acceleration in

the first few seconds of the takeoff ground roll. This would allow the Captain more time to correct the problem, or to abort the takeoff with ample runway left to stop. According to the NTSB and the airline pilots, this would greatly reduce the number of fatal takeoff accidents.

CHAPTER III

OPTIMIZED PERFORMANCE OF IMPAIRED AIRCRAFT

For flight under normal conditions during climb, cruise, and descent, many tables of optimized performance have been prepared some recently using the mathematical method of calculus of variations.^{2,37,42,76,79,80} However, if an aircraft becomes impaired due to damage or malfunction, there are no tables to consult for performance penalties. The crew simply estimates the flight performance penalty due to the impairment. The potential inaccuracy of the estimated performance loss can add considerable crew stress to an already stressful situation. FLES could be used to assess performance penalties, and to provide flight customized data under conditions of aircraft impairment. All of the airline pilots that were consulted agreed that this function of FLES would alleviate pilot stress, hence workload, and greatly enhance flight safety. If a commercial transport should become impaired while in climb or descent, the Captain would elect to land at the nearest available airport. However, during cruise the nearest available airport may be a considerable distance. For an impaired aircraft in cruise, performance optimization could be critical.

3.1 RANGE AND ENDURANCE

Calculus of variations is required only for the optimization of accelerating aircraft. Since the majority of airline flight takes place during steady, or quasi-steady conditions, calculus of variations is not necessary, however it has been used by some commercial airlines to reduce fuel costs. By using the calculus of variations fuel savings of up to 3% per flight can be achieved in the optimization of transport climb-cruise-descent performance. While these savings per flight are not impressive, the cumulative impact of a consistent small gain is significant.⁷⁶ For the calculus of variations optimized flight profiles of the TCV aircraft the reader is referred to reference 72.

For an impaired aircraft, the small gain per flight in fuel savings obtained using the complicated method of calculus of variations is not warranted. Since aircraft impairment is treated here, integral performance is sufficient.

The endurance of an aircraft is the maximum time that it can fly on a given amount of fuel. For endurance

$$E \equiv \int dt \quad (8)$$

$$dt = - \frac{dW}{c T} \quad (9)$$

$$E = \int_{W_1}^{W_0} \frac{dW}{c \cdot T} \quad (10)$$

During cruise

$$T = D = C_D^{1/2} \rho v^2 S = \frac{W C_D}{C_L} \quad (11)$$

Substituting into Equation (10), assuming small weight change increments, and integrating,

$$E = \frac{1}{c} \cdot \frac{C_L}{C_D} \ln \frac{W_0}{W_1} \quad (12)$$

(Endurance in hours; c in lb/lb of thrust-hr)

It can be seen that for a constant SFC at a given altitude, the endurance will be maximized when the C_L / C_D ratio is maximized.

Maximum C_L / C_D corresponds to a speed to be flown for maximum endurance. If the crew required a maximum endurance speed under normal conditions (such as in a holding pattern), FLES could provide this from stored endurance tables. However, in the event of aircraft impairment due to damage or malfunction, there are no on-board tables to consult. If aircraft impairment was

coupled with a weather emergency, which required the aircraft to remain airborne for a longer period of time, the crew would need a maximum endurance speed. FLES could easily provide this, as shown below (Section 3.3).

Range is the distance that an aircraft can fly on a given amount of fuel. One objective during normal cruise is to maximize this distance. The optimum flight path depends on the aerodynamic coefficients.

$$R \equiv \int ds = \int V dt. \quad (13)$$

The rate of change of aircraft weight is equal to the rate at which fuel is consumed and is given by

$$\frac{dW}{dt} = -c T; \quad dt = -\frac{dW}{c T} \quad (14)$$

Substituting into Equation (13),

$$R = \int V \left(-\frac{dW}{c T} \right) = \int_{W_1}^{W_0} \frac{V dW}{c T} \quad (15)$$

When the SFC is constant along the cruise trajectory, there are three ways to maximize Equation (15):

- Case I Constant Speed
- Case II Constant Engine Setting
- Case III Constant Altitude.

Case I Constant Speed:

Looking at the basic lift equation for equilibrium cruise,

$$L = C_L \frac{1}{2} \rho v^2 S = W.$$

For a constant C_L and true airspeed or Mach number, as the aircraft's fuel is consumed ρ must decrease, which implies that the aircraft will gain altitude. For airliners this method of flight would cause traffic control problems. Equation (15) would become

$$R = V \int_{W_1}^{W_0} \frac{dW}{c T} = V \int_{W_1}^{W_0} \frac{C_L dW}{c W C_D}$$

since

$$T = W \frac{C_D}{C_L}$$

from Equation (11). Integrating,

$$R = \frac{V}{c} \frac{C_L}{C_D} \ln \frac{W_0}{W_1} \quad (16)$$

It can be seen that for a constant speed cruise, maximum range occurs where L / D is a maximum.

Case II Constant Engine Setting:

For a constant engine setting, as the weight is reduced by

the consumption of fuel, the altitude will increase and the speed will increase. At a given engine rpm, engine performance in the stratosphere (where temperature is constant for certain levels) is such that thrust is directly proportional to air density and specific fuel consumption remains constant. Usually net thrust may be considered independent of speed (at subsonic speeds) over a limited speed band.⁸⁶ For airliners this method of flight would again cause traffic control problems because of the increase in altitude. Equation (15) would become,

$$R = \int_{W_1}^{W_0} \frac{V}{c} \frac{C_L}{W} \frac{dW}{C_D} .$$

Since

$$V = \left(\frac{2 T}{\rho S C_D} \right)^{1/2}$$

this becomes

$$R = \frac{1}{c} \frac{C_L}{C_D} \left(\frac{2 T}{\rho S} \right)^{3/2} \int_{W_1}^{W_0} \frac{1}{W} dW \quad (17)$$

Thus, the condition for maximum range in the stratosphere at a given engine setting occurs when

$L / D^{3/2}$ is a maximum, or $L^{2/3} / D$ is a maximum.

Case III Constant Altitude:

This case has been adopted by the airlines to facilitate enroute traffic control. In this case, as the fuel is consumed and the weight and lift decrease, the velocity is decreased. For constant altitude equilibrium cruising flight, Equation (11) gives,

$$T = W \frac{C_D}{C_L} \quad \text{and} \quad V = \sqrt{\frac{2W}{C_L \rho S}}$$

Substituting these expressions into Equation (15),

$$R = \int_{W_1}^{W_0} \frac{\sqrt{\frac{2W}{C_L \rho S}}}{c \left(\frac{W C_D}{C_L} \right)} dW$$

Simplifying,

$$R = \int_{W_1}^{W_0} \frac{1}{c} \sqrt{\frac{2}{\rho S}} \left(\frac{C_L^{1/2}}{C_D} \right) \frac{dW}{\sqrt{W}} \quad (18)$$

Integrating,

$$R = \frac{2}{c} \sqrt{\frac{2}{\rho S}} \left(\frac{C_L^{1/2}}{C_D} \right) \left[\sqrt{W_0} - \sqrt{W_1} \right] \quad (19)$$

It can be seen that for the constant altitude case, the best

range is obtained when the aircraft flies at a speed corresponding to the maximum ratio of $C_L^{1/2} / C_D$. Since density appears in the denominator, an airliner's range can also be improved at higher altitudes in an emergency. The effect is augmented by the improved fuel consumption obtained at altitude up to a critical altitude.

Summarizing, maximum range during cruise can be obtained by:

Constant Speed and L / D maximum

Constant Engine Setting and $L^{2/3} / D$ maximum

Constant Altitude and $L^{1/2} / D$ maximum.

In all sections below, only case III of constant altitude maximized range, applicable to airliners, will be considered. As noted above, for this case $C_L^{1/2} / C_D$ is to be maximized during normal flight. However, in certain conditions of impaired flight the range may also be increased by requesting a higher altitude from air traffic control (ATC), since ρ appears in the denominator. FLES could be used to assist in making choices where choices are available. If the crew required a maximum range speed under normal conditions, FLES could provide this from stored range tables. However, if aircraft impairment was coupled with an

unavailable airport, the crew may need impaired aircraft range information which FLES could provide as shown below (Section 3.2).

While the wind has no effect on the maximum endurance, it does affect the range. The analytic expression that could be used by FLES to calculate range when the wind is included is

$$R_W = \frac{2}{c} \sqrt{\frac{2}{\rho} S} \left(\frac{C_L}{C_D} \right)^{1/2} \left[\sqrt{W_0} - \sqrt{W_1} \right] \pm \frac{1}{c} \left(\frac{C_L}{C_D} \right) \ln \left(\frac{W_0}{W_1} \right) \quad (20)$$

where

- V_W = headwind velocity

+ V_W = tailwind velocity

FLES could obtain the wind velocity components from the navigational computer.

Summarizing, the speed for maximum range corresponds to the speed at which $C_L^{1/2} / C_D$ is a maximum. The speed for maximum endurance corresponds to the speed at which C_L / C_D is a maximum. For a parabolic drag polar, the maximum range

speed is always greater than the maximum endurance speed.

In low speed flight C_L and C_D are functions of α and flap setting. In high speed flight they become a function of α and Mach number. The values of C_L and C_D must be corrected for compressibility. This can be done by correcting the dynamic pressure. Incompressible dynamic pressure is equal to

$$q = 1/2 \rho v^2 \quad (21)$$

Compressible dynamic pressure is equal to

$$q_c = q \left[1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \dots \right] \quad (22)$$

As an example calculation, suppose in cruise

$$h = 30,000 \text{ ft.}$$

$$\rho = 8.9068 \times 10^{-4} \text{ lb-sec}^2 / \text{ft.}^4$$

$$V = .78 M = 775.983 \text{ ft/sec}$$

$$V_w = -100 \text{ mph}$$

$$S = 980 \text{ ft}^2$$

$$c = .798 \text{ lb/hr-lb} = 2.2167 \times 10^{-4} \text{ lb/sec-lb} = \text{SFC}$$

$$T = 8600 \text{ lb.}$$

$$W_o = 97,000 \text{ lb.}$$

$$W_1 = 77,000 \text{ lb.}$$

Using

$$T = q_c C_D S \quad \text{and} \quad W = q_c C_L S, \quad (23)$$

$$C_L = .318 \quad \text{and} \quad C_D = .0282.$$

Substituting the above into Equations (12) and (20),

$$E = 3.26 \text{ hours}; \quad R = 1431 \text{ miles.}$$

If the aircraft should suddenly become impaired, FLES could be used to instantly provide on a CRT display the speed to fly for either maximum range or maximum endurance depending on crew request. That is, the crew would have only to push a "Maximum Range" or a "Maximum Endurance" selector. Then FLES could provide the appropriate information by making the instantaneous calculations as shown below.

3.2 FLES OPTIMIZED RANGE

Suppose, that during cruise at 30,000 ft. over an ocean, an airliner's fuselage becomes ruptured. In addition to monitoring the rapid decompression, FLES could determine the new values of C_L and C_D . FLES could be programmed to automatically generate new aerodynamic coefficients if rapid decompression should occur.

At the instant of rupture, the FLES velocity monitor might read that the velocity had dropped from 775.983 ft/sec to 656.070 ft/sec. After the air jet exhausting from the

cabin had reached zero velocity, (FLES is monitoring the cabin pressure) FLES could use the stabilized aircraft velocity, which it might read as 694.320 ft/sec to calculate the stabilized aerodynamic coefficients. Using Equations (22) and (23),

$$q_c = q (1.128^+); \quad C_L = .409; \quad C_D = .0363$$

after stabilization. Using $e = .7$, $AR = 8.83$, and Equation (6),

$$C_{D_{\text{ruptured aircraft}}} = .0278. \quad (24)$$

Under the conditions of the ruptured fuselage both C_L and C_D have changed, because the drag of the aircraft has increased, and the velocity has decreased. Although C_L and C_D have both changed, the ratio of C_L / C_D has not changed. From Equation (23),

$$C_L = \frac{W}{q_c S} \quad \text{and} \quad C_D = \frac{T}{q_c S} .$$

The ratio of

$$C_L / C_D = \frac{W}{T} .$$

With no change in throttle setting, and no change in altitude, this ratio will be the same before and after the

rupture. Therefore, from the endurance equation, Equation (12),

$$E = \frac{1}{c} \frac{C_L}{C_D} \ln \frac{W_0}{W_1} = 3.26 \text{ hours}$$

as before the rupture. The effect of the increased fuselage drag is similar to the effect of an increased headwind and does not alter the length of time that the engines will run on a given amount of fuel for a given altitude, power setting, and set of aircraft weights.

However, if the aircraft continued its flight under these conditions, the range would decrease since the ratio of $C_L^{1/2} / C_D$ does change. The range equation, Equation (20), gives the new range as

$$R = 1222 \text{ miles,}$$

a decrease of 15 % on the same fuel. Although the aircraft can still fly for the same length of time, the hole in the fuselage has reduced the range since,

$$C_L^{1/2} / C_D \text{ before the rupture} = 20 \rightarrow R = 1431 \text{ miles.}$$

$$C_L^{1/2} / C_D \text{ after the rupture} = 17.62 \rightarrow R = 1222 \text{ miles.}$$

If the nearest available airport was a considerable

distance, FLES could use the generated aerodynamic coefficients to calculate the performance penalties. At this altitude the range performance penalty is a 15 % decrease. However, in this type of flight emergency the aircraft would most likely descend to a lower altitude as soon as possible. The altitude selected would be dictated by the pressurization constraints. Once the altitude was selected, FLES could determine the conditions to achieve the best range. That is, FLES could use the generated impaired aircraft aerodynamic coefficients to optimize the range by maximizing the ratio of $C_L^{1/2} / C_D$.

The mechanics of how this would be done follow. From Equation (6) for a parabolic drag polar,

$$C_D = C_{D_0} + K C_L^2$$

where C_{D_0} and K are both known constants for the aircraft. Thus, C_D is a function of C_L , and

$$\frac{C_L^{1/2}}{C_D} = \frac{C_L^{1/2}}{C_{D_0} + K C_L^2} \quad (25)$$

The condition for maximum range is that Equation (25) be a maximum. Since C_L is the independent variable in the

parabolic drag polar equation, and C_D is the dependent variable, the derivative is taken with respect to C_L . Equation (25) will have an extremum (maximum, minimum, or inflection point) where the derivative with respect to C_L is equal to zero. That is,

$$\frac{\partial \left(\frac{C_L^{1/2}}{C_D} \right)}{\partial C_L} = \frac{1/2 C_L^{-1/2} (C_{D_0} + K C_L^2) - C_L^{1/2} (2 K C_L)}{(C_{D_0} + K C_L^2)^2} =$$

$$\frac{1/2 C_{D_0} C_L^{-1/2} - 3/2 K C_L^{3/2}}{(C_{D_0} + K C_L^2)^2} = 0. \quad (26)$$

To show that this extremum is a maximum,

$$\frac{\partial^2}{\partial C_L^2} \left(\frac{C_L^{1/2}}{C_D} \right) \text{ must be negative.}$$

$$\frac{\partial^2}{\partial C_L^2} \left(\frac{C_L^{1/2}}{C_D} \right) = \frac{\partial}{\partial C_L} \left[\frac{1/2 C_{D_0} C_L^{-1/2} - 3/2 K C_L^{3/2}}{(C_{D_0} + K C_L^2)^2} \right] =$$

$$\begin{aligned}
& \frac{(-1/4 C_{D_o} C_L^{-3/2} - 9/4 K C_L^{1/2})(C_{D_o} + K C_L^2)^2}{(C_{D_o} + K C_L^2)^4} \\
& \frac{(1/2 C_{D_o} C_L^{-1/2} - 3/2 K C_L^{3/2})^2 (C_{D_o} + K C_L^2)(2 K C_L)}{(C_{D_o} + K C_L^2)^4} = \\
& \frac{-(1/4 C_{D_o} C_L^{-3/2} + 9/4 K C_L^{1/2}) C_D}{C_D^3} \\
& \frac{-(1/2 C_{D_o} C_L^{-1/2} - 3/2 K C_L^{3/2})(4 K C_L)}{C_D^3} \quad (27)
\end{aligned}$$

Equation (27) is negative, since the first term is clearly negative, and the first parenthesis in the second term has been set to zero in Equation (26). Therefore, Equation (26) is a maximum. Solving Equation (26),

$$C_{D_o} = 3 K C_L^2 \quad (28)$$

For the TCV aircraft, $K = .0515$ and Equation (28) becomes,

$$C_{D_o} = .1545 C_L^2 \quad (29)$$

From Equation (24),

$$C_{D_{\text{ruptured aircraft}}} = .0278.$$

Substituting this value into Equation (29),

$$C_{L_{\text{Max Range}}} = .4242. \quad (30)$$

Substituting into Equation (6),

$$C_D = .0278 + .0515 (.4242)^2 = .03707. \quad (31)$$

Suppose the flight was continued at an altitude of 15,000 ft. where,

$$\begin{aligned} \rho &= .0014962 \text{ lb-sec}^2 / \text{ft}^4 \\ a &= 1057.4 \text{ ft/sec} = \text{local speed of sound} \\ V_w &= - 70 \text{ mph} \\ \text{SFC} &= .84 . \end{aligned}$$

Substituting the above values into

$$C_L = \frac{W}{q_c S} ,$$

$$q_c = \frac{97,000 \text{ lb}}{.4242 (980) \text{ ft}^2} = 233.332 \text{ lb/ft}^2 =$$

$$\frac{1}{2} \rho V^2 \left[1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \dots \right] , \text{ or}$$

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$$V^2 \left[1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \dots \right] = 311,900 \text{ ft}^2/\text{sec}^2.$$

Solving,

$$V_{\text{Max Range}} = 539 \text{ ft/sec } (.51M)$$

at the selected altitude.

To calculate the maximum range for the aircraft FLES would use Equation (20). From

$$C_L^{1/2} / C_D = 17.57, \quad C_L / C_D = 11.44, \text{ and}$$

Equations (20) and (12),

$$\text{Range} = 912 \text{ miles;} \quad \text{Endurance} = 3.16 \text{ hours.}$$

Thus, if the crew selected maximum range, FLES would display

$$" \quad V_{\text{Max Range}} = .51 M; \quad R = 912; \quad E = 3.16 \quad "$$

on a CRT and allow the impaired aircraft a greater chance to safely reach an airport.

3.3 FLES OPTIMIZED ENDURANCE

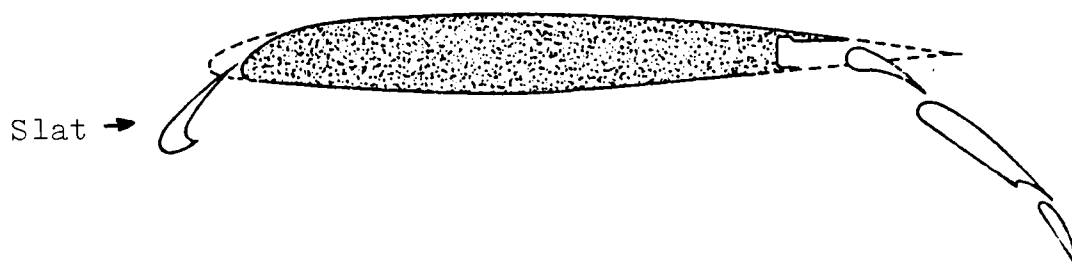
Flight performance could also be penalized by a malfunction that might not require an immediate landing, such as a control surface malfunction. With the use of complex high lift devices (see Figure 3), and the increased



TAKEOFF: Large Wing Area; High Lift; Low Drag.



CRUISE: High Speed; Low Drag.



LANDING: Larger Wing Area; Higher Lift;
Stable Approach Platform; Higher Drag.

Figure 3. TCV Aircraft High Lift System.

flight control activity due to the use of active controls, a control surface malfunction is an increased possibility. Sensors located on each control surface could provide continuous status information to FLES (see Section 2.1). For example, slats, which move more slowly than flaps or spoilers, have sensors which detect in-transit states in addition to extended or retracted positions. Slats normally extend automatically before the flaps, as the pilot extends the flaps. However, the crew is provided with a disconnect switch that disengages the slats from the flaps in emergency situations.^{11,88} Before any flight control asymmetries could be corrected, the Captain would need to know quickly exactly which surfaces were malfunctioning. FLES could communicate this information instantly by a pictorial CRT display with the inoperative, or out of position controls flashing.

Suppose that while in cruise at 30,000 ft., a right trailing edge (T.E.) inboard flap was suddenly to extend. FLES could instantly convey this to the crew with a CRT display as seen in Figure 4 with the right T.E. inboard flap section flashing. FLES could also display the amount of flap extension which it could obtain from the flap position sensor. Rapid presentation of control surface malfunction information would allow the Captain to correct the asymmetric flight condition by quickly extending the corresponding left T.E. inboard flap.

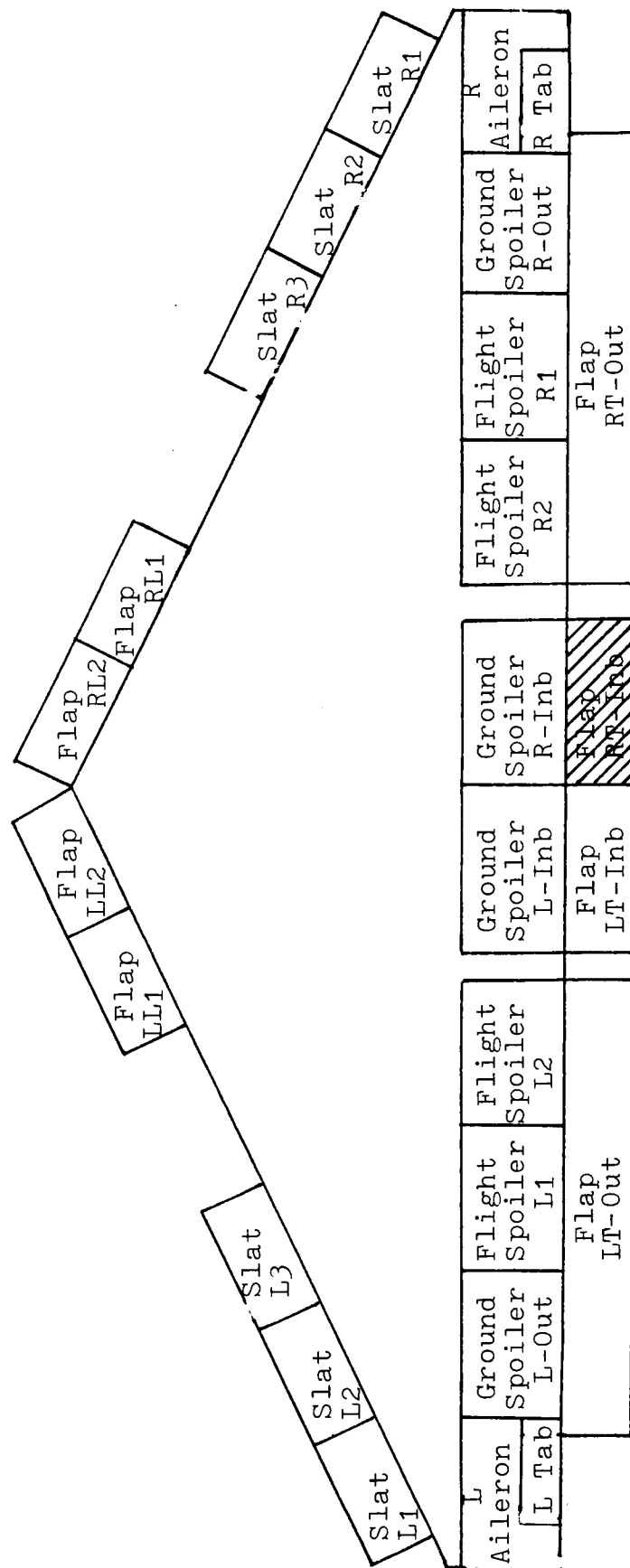


Figure 4. Status Display to Crew of TCV Wing Control Surfaces.

Table 3. Wing Control Surface Designations of Figure 4.

FLAPS

LL 1 = Left Leading Edge 1
 LL 2 = Left Leading Edge 2
 RL 1 = Right Leading Edge 1
 RL 2 = Right Leading Edge 2
 RT-Out = Right Trailing Edge Outboard
 RT-Inb = Right Trailing Edge Inboard
 LT-Out = Left Trailing Edge Outboard
 LT-Inb = Left Trailing Edge Inboard

SLATS

L 1 = Left 1
 L 2 = Left 2
 L 3 = Left 3
 R 1 = Right 1
 R 2 = Right 2
 R 3 = Right 3

FLIGHT SPOILERS

R 1 = Right 1
 R 2 = Right 2
 L 1 = Left 1
 L 2 = Left 2

GROUND SPOILERS

R-Out = Right Outboard
 R-Inb = Right Inboard
 L-Out = Left Outboard
 L-Inb = Left Inboard

Thus, the yaw and bank produced by the asymmetry could be quickly checked.

Although the flight asymmetry could be corrected by deployment of the corresponding opposite wing surface, the drag would be doubled. In the case of inboard surfaces, the Captain may have choices. Without FLES the Captain may extend the corresponding flap and estimate intuitively the doubled drag, then guess the performance penalties associated with both flaps extended versus asymmetric flight. FLES could be used to assist in this type of choice by generating aerodynamic coefficients for both the one-flap-extended case and the two-flap-extended case. Then FLES could be used to assess the performance penalties in each case.

If this flight situation was coupled with a weather emergency, which made the endurance the priority parameter, the crew could instruct FLES to maximize the endurance by selecting "Max Endurance." FLES could then provide the correct speed to fly for maximum endurance by optimizing the endurance performance of the impaired aircraft. While manufacturer's tables are available for drag increments due to normal control surface configurations, there are none available to the crew for abnormal control surface configurations. FLES could begin by calculating the increased basic (zero lift) drag of the aircraft.

Suppose the aircraft at 30,000 ft. with both flaps

extended was at a point in its flight where 10,000 lb. of its fuel had already been consumed. That is,

$$\begin{aligned}\rho &= 8.9068 \times 10^{-4} \text{ lb-sec}^2 / \text{ft}^4 \\ a &= 994.85 \text{ ft/sec} \\ V_w &= -100 \text{ mph} \\ c &= .798 \text{ lb/hr-lb} = \text{SFC} \\ T &= 8600 \text{ lb} \\ W_0 &= 87,000 \text{ lb} \\ W_1 &= 77,000 \text{ lb}\end{aligned}$$

After the aircraft had been stabilized, FLES might read the velocity as

$$V = 621.8 \text{ ft/sec} \quad (.625 \text{ M}).$$

FLES could then calculate q_c from

$$q_c = 1/2 \rho V^2 \left[1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \dots \right]$$

and using Equations (23), and (12),

$$q_c = 189.66 \text{ lb/ft}^2; \quad C_L = .468; \quad C_D = .0463;$$

$$\text{and} \quad E = 1.55 \text{ hours}$$

at this speed. To optimize the endurance FLES must determine the basic drag. Using Equation (6),

$$C_{D_0} = .0463 - .0515 (.468)^2 = .0350 \quad (32)$$

The endurance of a flight is maximum when the ratio of C_L / C_D is maximized according to Equation (12). This ratio has an extremum when the derivative with respect to C_L , the independent variable, is set to zero. That is,

$$\frac{\partial}{\partial C_L} \left(\frac{C_L}{C_D} \right) = 0. \quad (33)$$

For a parabolic drag polar,

$$\frac{C_L}{C_D} = \frac{C_L}{C_{D_0} + K C_L^2} \quad . \quad \text{So,}$$

$$\frac{\partial}{\partial C_L} \left(\frac{C_L}{C_D} \right) = \frac{(C_{D_0} + K C_L^2) - C_L (2 K C_L)}{(C_{D_0} + K C_L^2)^2} =$$

$$\frac{C_{D_0} - K C_L^2}{(C_{D_0} + K C_L^2)^2} = 0. \quad (34)$$

To show that this extremum is a maximum,

$$\frac{\partial^2}{\partial C_L^2} \left(\frac{C_L}{C_D} \right) \text{ must be negative.}$$

$$\frac{\partial^2}{\partial C_L^2} \left(\frac{C_L}{C_D} \right) = \frac{-2K C_L C_D^2 - (C_{D_0} - K C_L^2) 2 C_D 2 K C_L}{C_D^4} =$$

$$\frac{-2K C_L C_D - 4K C_L (C_{D_0} - K C_L^2)}{C_D^3} \quad (35)$$

The first term of Equation (35) is clearly negative. The parenthesis in the second term has been set equal to zero by Equation (34), thus, Equation (34) gives a maximum point.

Solving Equation (34),

$$C_{D_0} = K C_L^2 \quad (36)$$

for maximum endurance. FLES could provide the crew with the speed to fly for maximum endurance by solving Equation (36) for the required C_L . Using $K = .0515$ and the

above value of C_{D_0} for the abnormally configured aircraft,
and Equation (6),

$$.0350 = .0515 C_L^2 \quad (37)$$

$$C_L = .8244; \quad C_D = .07700; \quad C_L / C_D = 11.78 \quad (38)$$

Using Equations (22) and (23),

$$V^2 \left[1 + \frac{M^2}{4} + \frac{M^4}{40} + \frac{M^6}{1600} + \dots \right] = \frac{241,804 \text{ ft}^2}{\text{sec}^2} \quad (39)$$

Solving,

$V_{\text{Max Endurance}} = .48 M$

The improvement in endurance at this speed using Equation (12) is

$$E_{\text{Max}} = 1.80 \text{ hours.}$$

Thus, if the crew requested a maximum endurance speed, due to a weather emergency, for the impaired aircraft, FLES could display

$$" \quad V_{\text{Max End}} = .48 M; \quad E_{\text{Max}} = 1.80 \quad "$$

FLES being able to determine and advise the crew on

speeds to fly for maximum range or maximum endurance during times of flight emergencies, would greatly reduce pilot stress, hence workload, and significantly enhance flight safety.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

An investigation has been conducted to determine possible uses of a flight expert system, FLES, for in-flight performance management of commercial transport aircraft. Advanced systems of the 1995 transport have been considered, together with the components and sensors of commercial transport internal systems. Conferences have been held with today's airline pilots to assess their current and future flight deck needs in terms of FLES capability. In order to manage the performance FLES would need data from all the aircraft systems which contained performance information.

4.1 CONCLUSIONS

- (1) Since future commercial transports will be flown by only two pilots, FLES could alleviate pilot workload by functioning as a Performance Flight Engineer and monitoring critical components of internal systems.
- (2) FLES could issue warnings on the pilots' CRTs when parameters went out of range. FLES could accommodate multiple malfunctions and prioritize them according to importance to the crew.

- (3) FLES could employ its predicting and diagnostic capabilities to present the cause and the corrective action for a particular in-flight malfunction.
- (4) FLES could be used to present all data that the pilots normally have to look up, such as EPR, N_1 , critical velocities, etc. FLES could use its information to intelligently solve problems where data must be rapidly revised due to a minor malfunction.
- (5) Flight safety would be greatly enhanced and airline takeoff accidents significantly reduced by FLES early detection and diagnosis of inadequate takeoff acceleration.
- (6) Since weight errors of 10 % sometimes occur on today's airliners, an Integral Weight and Balance System (IWBS) is a requirement for the success of accurate takeoff performance management. The IWBS could also provide accurate cg information, which would allow many other FLES performance calculations.
- (7) Tire pressures and cargo door sealing are examples of additional information on aircraft takeoff status that could be provided to FLES by additional sensors.

- (8) FLES could be used to assess in-flight performance penalties, and optimize the performance of an impaired aircraft.
- (9) FLES could rapidly determine the best choice of action in a multiple choice flight situation.

4.2 RECOMMENDATIONS

- (1) Due to weight errors in airline Load Manifests, an IWBS is a requirement for the successful takeoff performance management.
- (2) The function of FLES should not be to command an abort, but rather to use its high speed detection and diagnostic capabilities to present information to the crew early enough in the takeoff roll so that the Captain could correct the problem, or make the decision to abort at low speeds with ample stopping distance.
- (3) FLES should not be used to take any decision making power away from the Captain, but rather to assist in making those decisions more quickly, and more efficiently by providing fast and accurate information.
- (4) Since the 1995 transport will use active control systems, hence increased control surface activity, an advanced performance management system should be able to accommodate control surface malfunctions.

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APPENDIXES

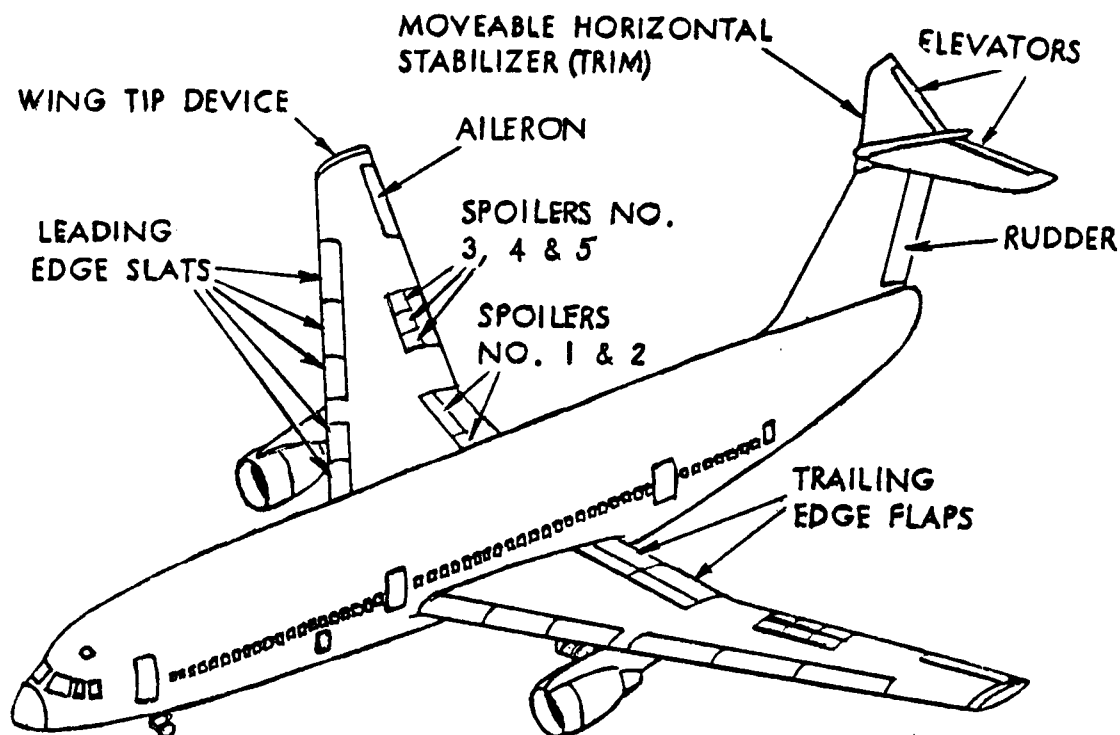
APPENDIX A. THE 1995 TRANSPORT AIRCRAFT

THE 1995 TRANSPORT AIRCRAFT

According to the Lockheed-Georgia Company study, the 1995 transport will be a 200 passenger, wide-body, two engine, two pilot aircraft with a range of 2500 nautical miles. The avionics include pilot Cathode Ray Tube (CRT) displays, holographic head-up displays, and multiplex data buses for communication between the computers and the aircraft systems. The aerodynamics include high aspect ratio (AR) wings, advanced airfoils, and movable wing tip devices. The 1995 transport will have no hydraulic systems. The flight controls will be operated by all-electric actuators and use active control systems.⁶⁹

To underline the complexity of future transport flight controls and expose the need for an advanced performance management system, the 1995 transport flight controls are described in more detail. The aircraft will employ the advanced technology of active control systems to enable it to use a lighter design structure for increased fuel efficiency (see Figure A1). Active control systems consist of: the stability augmentation system (SAS); maneuvering load alleviation; gust load alleviation; and flutter suppression systems. With these systems implemented the aircraft can realize increased performance by reduced drag and weight.

For example, when the static stability is relaxed,



Active Control System Function	Control Surface
Pitch Stability Augmentation (PSAS)	Elevator
Active Lift Distribution Control (ALDC)	Elevator Aileron
Lateral Stability Augmentation (LSAS)	Aileron
Roll Control Spoilers (RCS)	Outboard Spoilers
Direct Lift Control (DLC)	Inboard Spoilers Outboard Spoilers
Ground Spoilers (GS)	Inboard Spoilers Outboard Spoilers
Speed Brakes (SB)	Inboard Spoilers Outboard Spoilers
Yaw Stability Augmentation (YSAS)	Rudder
Rudder Limiter (RL)	Rudder
Wing Torsion Relief	Wing Tip Device

Figure A1. Active Control Systems of 1995 Transport.

the empennage can be designed smaller. The SAS then artificially stabilizes the aircraft. When a flutter suppression system is used, the wing structure can be lightened. This system moves the wing control surfaces to expand the flight envelope. When maneuvering and gust load alleviation systems are used, components of the entire structure can be lightened. These load alleviation systems will also provide airline passengers a smoother ride by minimization or elimination of turbulence effects. These systems shift the spanwise center of pressure inboard to reduce wing bending moments through aileron and flap deflections. (For a more detailed account of these systems the reader is referred to NASA Report 165 631 by Boeing, October 1981.) All of the active control systems function automatically by governing control laws through the aircraft flight control surfaces.

The all-electric flight control surfaces (see Figure A2) on each wing include: three outboard slats, and three inboard slats located on the leading edge (L.E.); three outboard spoilers, three outboard flaps, one outboard aileron, one outboard aileron trim tab, two inboard spoilers, and two inboard flaps located on the trailing edge (T.E.); and the movable winglet located on the wing tip.⁶⁹ Table A1 shows that on the wing alone there are a total of 38 control surfaces to be managed. These control surfaces operate both conventionally and non-conventionally.

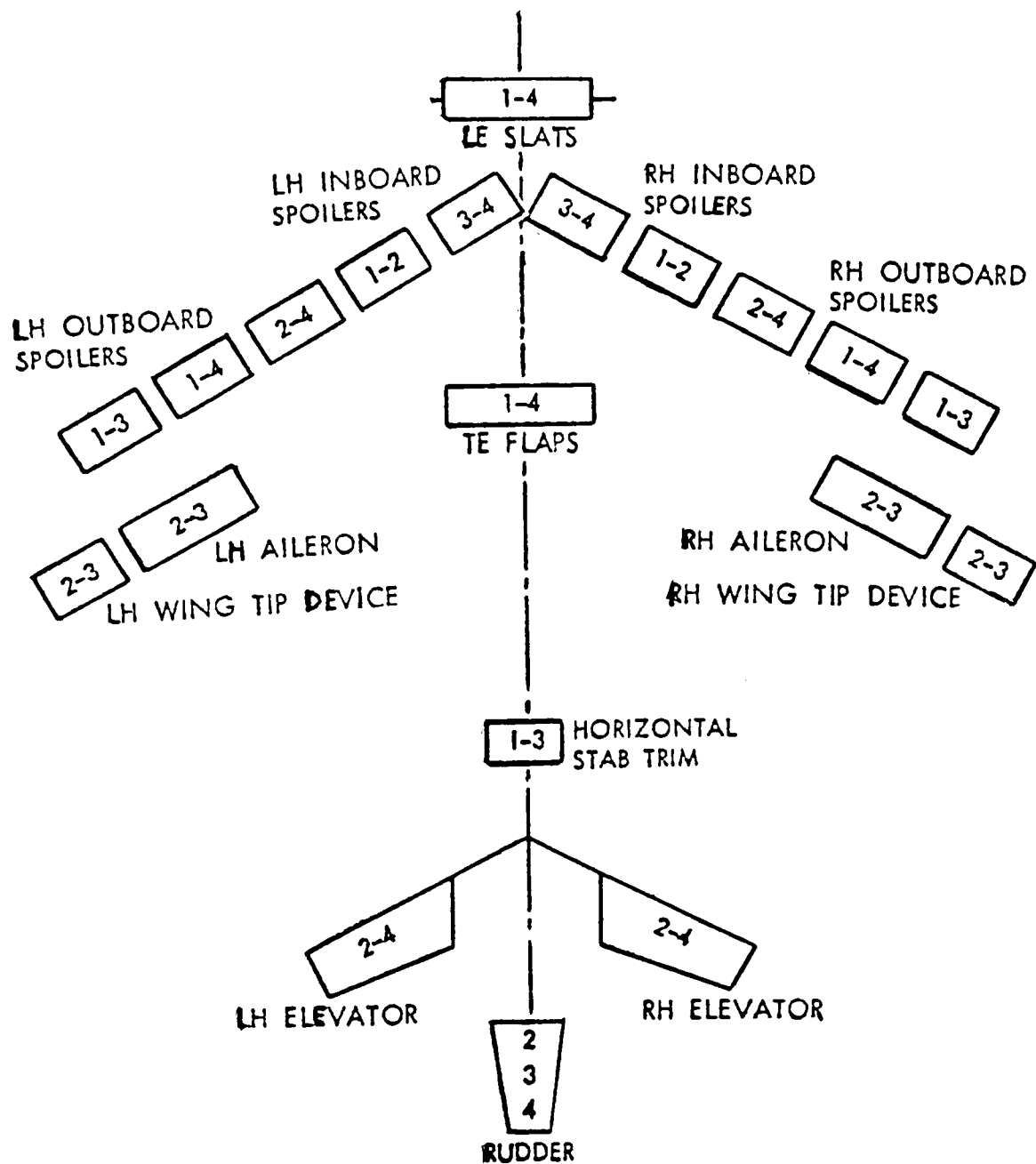


Figure A2. 1995 Transport All-Electric Flight Controls.

Table A1. 1995 Transport Wing Control Surfaces.

12	Leading Edge Slats
10	Spoilers
10	Trailing Edge Flaps
2	Ailerons
2	Aileron Trim Tabs
2	Winglets
38	Wing Control Surfaces

For example, the outboard spoilers operate differentially for roll control and symmetrically with the inboard spoilers as speed brakes, as ground spoilers, and as direct lift control devices. Similarly, the ailerons not only operate differentially for roll control, but also symmetrically to modify the spanwise loading, thereby reducing wing bending moments.

Active control systems may use more flight control surfaces, both conventional and non-conventional operation, and increased control surface activity. Therefore, chances of control surface malfunctions will be greater. An advanced in-flight performance management system should be able to accommodate a control surface malfunction and assess the associated performance penalties.

APPENDIX B. THE TCV AIRCRAFT

THE TCV AIRCRAFT

The aircraft used in this investigation is the NASA Langley TCV, which is a highly modified Boeing 737 research aircraft. The TCV has been chosen as the example aircraft because it has been modified to incorporate 1995 transport concepts, and because it is used to evaluate new flight management systems for transport aircraft.

The basic aircraft has been modified to allow fly-by-wire operation of the primary flight controls, flaps, slats, spoilers, and throttles through electrically commanded servos. The flight controls can be operated automatically when the commands are issued to servos according to the governing control laws.⁵⁴

Wing flight control surfaces on the TCV include: three outboard slats, and two inboard Krueger flaps located on the L.E.; one outboard triple-slotted flap, two outboard flight spoilers, one outboard ground spoiler, one outboard aileron, one outboard aileron trim tab, one inboard triple-slotted flap, and one inboard ground spoiler located on the T.E. (see Figure B1). The flight control surfaces can be operated automatically through governing control laws, or manually by either the forward or the aft flight crew.

The aircraft has both a forward flight deck (FFD) for two safety pilots, and an aft flight deck (AFD) for two evaluation pilots who assess new management systems.

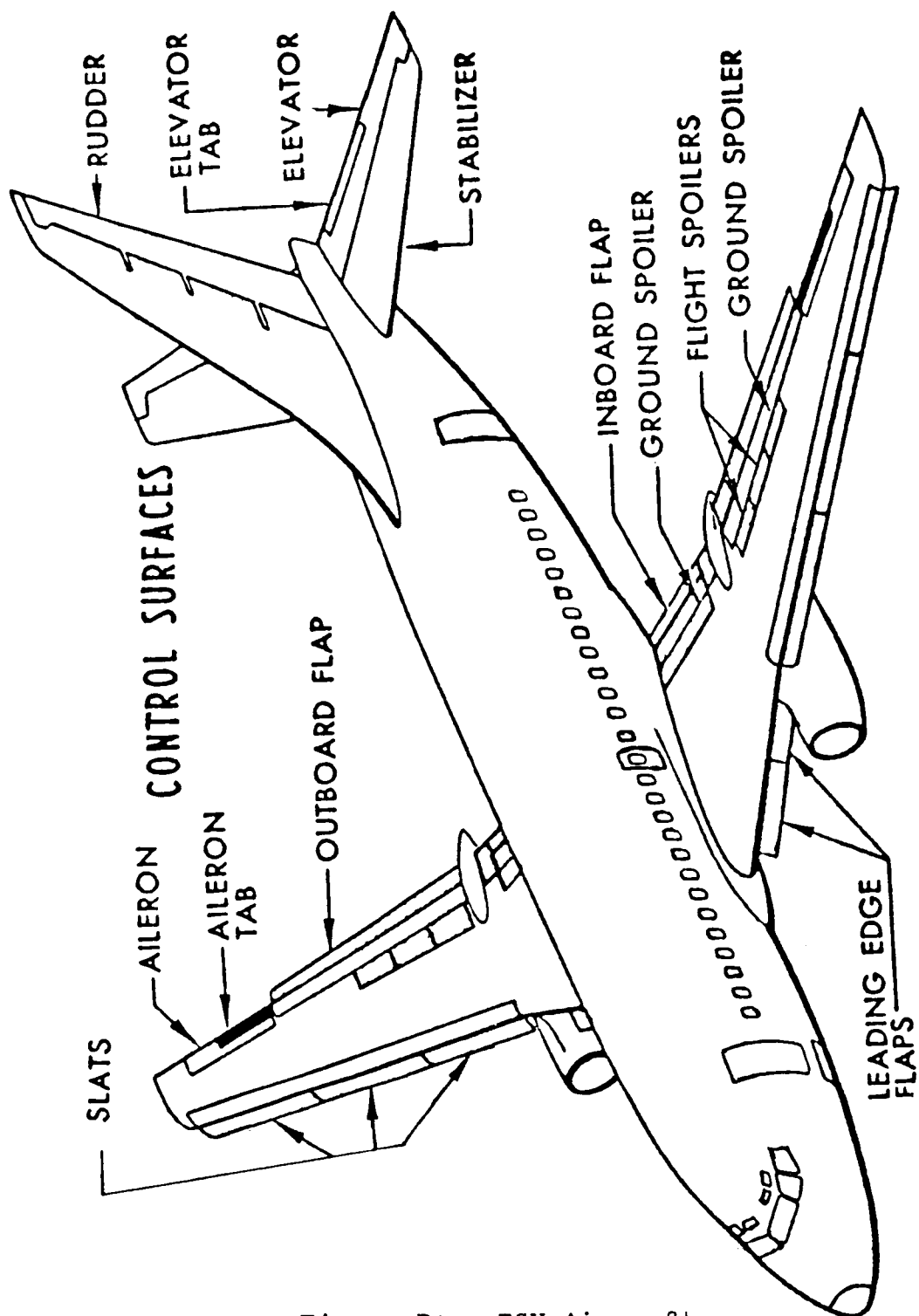


Figure B1. TCV Aircraft

The AFD is located in the passenger cabin 20 feet aft of the standard flight deck. The AFD (see Figure B2 and Figure B3) includes three CRT displays for each pilot, one of which can access information from the navigational computer such as Standard Instrument Departure (SID), Standard Terminal Arrival Route (STAR), and terminal airport runway data.^{83,84} Should the new system being evaluated malfunction, the FFD safety pilots can take control of the aircraft, at any time, by overpowering the AFD controls or by disengaging the AFD.⁵⁴

The TCV is equipped with an extensive data acquisition system, therefore 1995 transport in-flight performance management systems and expert systems can be evaluated.

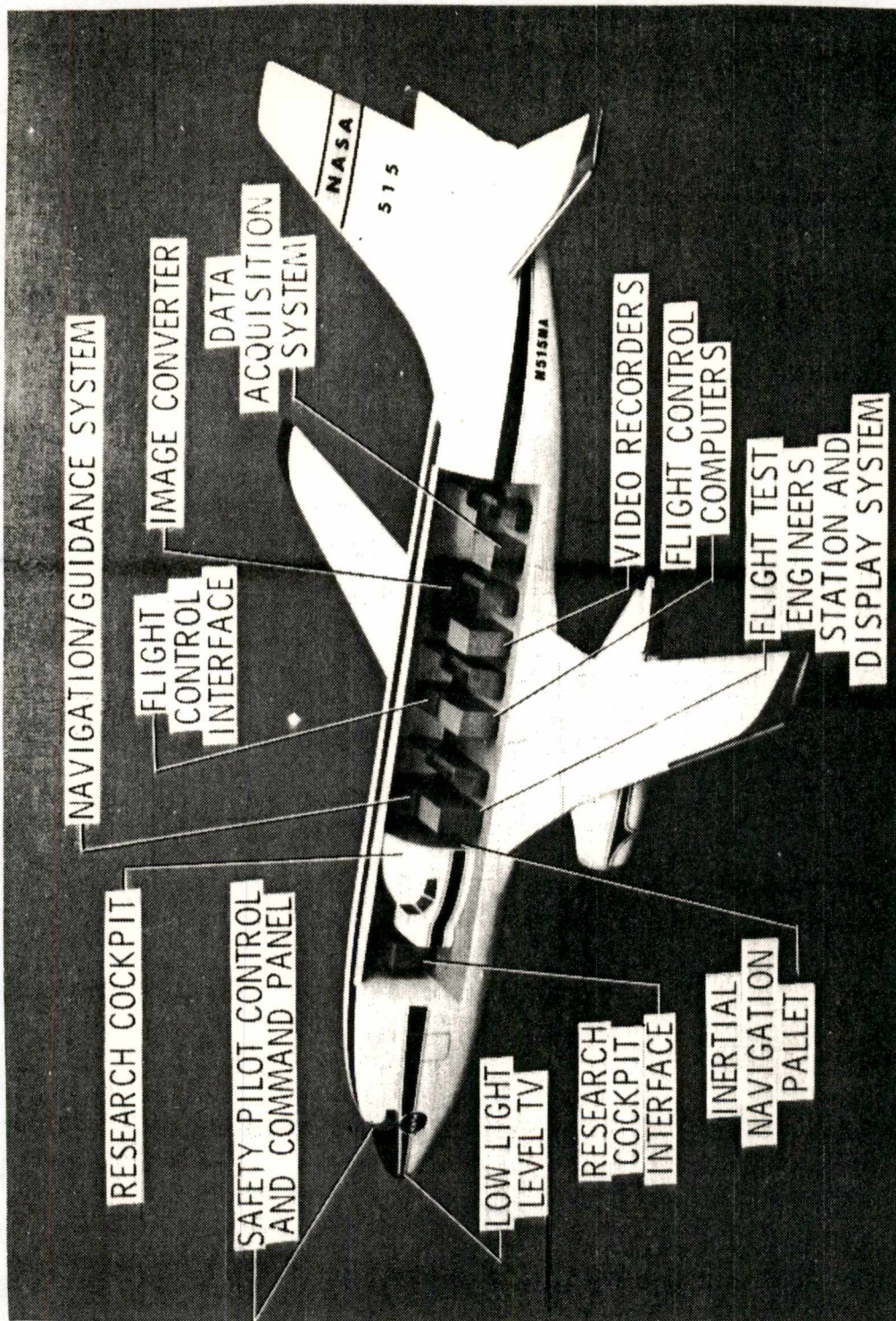


Figure B2. NASA TCV B-737 Research Aircraft (Internal).

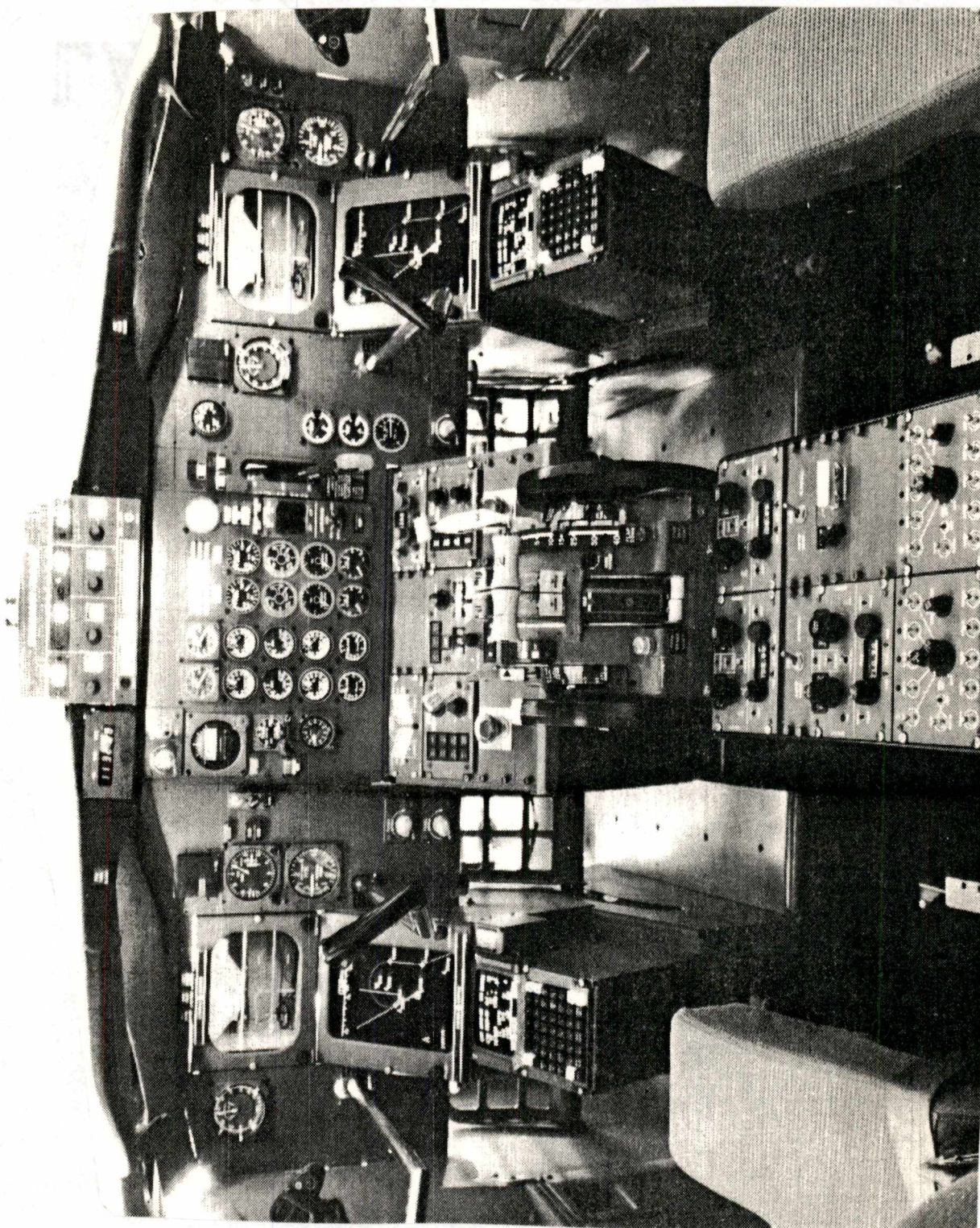


Figure B3. TCV Aft Flight Deck Display Arrangement.

VITA

Chris Barret was born and raised in Cleveland, Ohio. She attended college at the Ohio University in Athens, Ohio and the Ohio State University in Columbus, Ohio where she graduated with a 3.5/4.0 and a Bachelor's degree in Aeronautical and Astronautical Engineering in 1983. She graduated with a 3.6/4.0 and a Master's degree in Aerospace Engineering from the University of Tennessee Space Institute in 1986.

Chris is a member of Tau Beta Pi National Engineering Honor Society, Sigma Gamma Tau National Honor Society in Aerospace Engineering, the American Institute of Aeronautics and Astronautics (AIAA), the Experimental Aircraft Association (EAA), the Soaring Society of America, the American Hovercraft Association, the American Helicopter Society, the Air Force Museum Foundation, the Aero Squadron Flying Club, the Smithsonian Associates, the American-Egyptian Friendship Society, and Flying Engineers International.

Chris has over 500 hours of flight time in land planes, seaplanes, sailplanes, aerobatic and experimental aircraft. She has flown balloons and taken parachute jump training and parachuted. She has taken the Air Force Physiological Training, experienced 25,000 ft. altitudes without oxygen, experienced rapid decompression, and taken Pilot Desert Survival Training. In 1978 and 1979 she organized a

Civil Engineering Study Tour to Egypt from the Ohio State University which studied the Pyramids, the Aswan High Dam, the Irrigation Systems of the Nile Delta, and the Suez Canal. At that time she was a guest of Egypt Air and given a plane to fly over the Sahara Desert.

She has also been a trainer of German Shepherd dogs for Obedience and Conformation Show. She has lived all over the U.S. and been to Athens, Rome, and Paris many times including on the Concorde to the Paris Air Show in 1983. She attends major air shows, trade shows and aerospace conventions regularly. She presented a paper at an AIAA Conference in Huntsville, Alabama in April of 1986.

Chris lives in a wilderness retreat on the mountain acreage she purchased in 1983 and conducts construction and civil engineering projects of her own there.

Chris definitely plans to earn her Ph.D. degree in Aerospace Engineering and hopes to specialize in Flight Dynamics. She has a strong interest in Stability + Control of low aspect ratio flight vehicles and flying wings.

Chris has accepted a position as Aerospace Engineer with the National Aeronautics and Space Administration George C. Marshall Space Flight Center in Huntsville, Alabama.