

IMPROVING COCKPITS THROUGH FLIGHT CREW WORKLOAD
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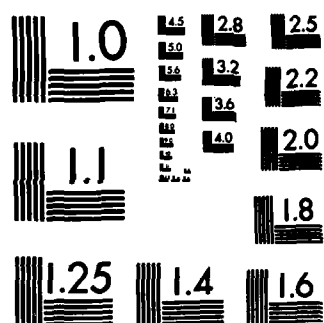
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IMPROVING COCKPITS THROUGH FLIGHT CREW WORKLOAD MEASUREMENT

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IMPROVING COCKPITS THROUGH CREW WORKLOAD MEASUREMENT

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ABSTRACT

The Human Factors Engineering Department in conjunction with the Advanced Design and Flight Development groups at the Douglas Aircraft Company is currently engaged in a project directed toward developing the capability to measure objectively the flight crew workload with sufficient sensitivity to differentiate between alternative crew station layouts, controls, and displays. The computerized technique concentrates on design factors under the control of crew station designers and provides for quick and low-cost iteration of alternatives. The program provides workload as related to specific equipments and systems, permitting special attention to be given to high workload items during the early development of concepts and hardware before simulation is available. The technique and program is also applicable to integrated displays, including those where programming to meet information requirements is an element.

The analysis is based on a typical flight mission scenario constructed to explore the expected operational envelope and to exercise a major portion of the aircraft displays, controls, and systems in a sequence and time frame typical of the more demanding operations planned. The primary measure is the ratio of the required performance time to the time available within the time constraints regulated by a specific flight, supplemented by hand movement action and distance data. The operating procedures are detailed for computer handling in a way that relates a single workload element to a single piece of equipment, with the equipment coded by its location and ATA number. The times for completing specific acts in the cockpit are developed by detailed analysis of each task and its associated equipment using standard action and reading times. The hand movement and distance data are developed using a full-size design aid.

Work is continuing on this project to develop techniques for evaluating more precisely the impact of abnormal and emergency procedures on flight crew workload and how to reduce it. An adaptation of Winger's function interface technique can be used to account for the known ability of pilots to handle the heavy workloads associated with emergency procedures, but still provide for an objectively measured baseline against which to evaluate proposed changes.

INTRODUCTION AND BACKGROUND

For several years the Douglas Aircraft Company has been conducting a program directed toward developing the ability to objectively measure flight crew workload with sufficient sensitivity to differentiate between alternate crew station configurations. This capability is considered essential to the Douglas goal of designing the most economic cockpits with acceptable and safe workloads. This development is a joint effort of the Human Factors Engineering, Advanced Design, and Flight Development groups at Douglas.

An objective measuring system for flight crew workload has been a long standing requirement of crew station designers. They need a system that is usable during the early design stages and provides a means for identifying both the peak workload periods and the specific crew station characteristics that contribute to these workloads. It must also be able to quickly evaluate proposed changes in crew station equipments or layouts to determine the degree to which undesirable workload peaks can be reduced. The workload measuring system that is in the development stage at Douglas is meeting these goals by providing a standard measuring tool for comparisons of alternative crew station configurations. Even while this measuring system is still being developed and refined, it is being used to assist in guiding crew station design concepts on new aircraft, both military and civilian. This close interface with crew station design engineers is also providing invaluable feedback that helps guide the development of the measuring system and ensures that it provides the type of information desired by the designers. An example of this was the recent inclusion of the various design group symbols so that these groups could see what proportion of the flight crew workload was their responsibility. It also provides the capability for showing how design group changes affect total flight crew workload as well as the proportional change in the specific area for which they are responsible.

DEFINITIONS OF FLIGHT CREW WORKLOAD

While there have been many symposia and papers devoted to flight crew workload, there seems to be no commonly accepted

definition of what is meant by this term. This is best illustrated by an incident at the Crew System Design Conference held in Los Angeles in September, 1972, in which one of the authors, during a discussion of flight crew workload, asked for a definition of it (Reference 1). One of the participants volunteered the idea that workload was the amount of effort expended in the performance of a task or tasks within certain established tolerances. Another thought that workload should be defined in terms of what is required to handle emergency situations. These seemed to be close enough for conference purposes and the discussions of flight crew workload continued.

Some of the definitions of workload contained in the literature include the following from Reference 2:

"Workload is commonly defined in terms of the quantity of work units to be performed in a given interval of time"

"The number of tasks accomplished in a block of time"

"Operator workload is often quantified in terms of input parameters rather than output measures."

At this same Crew System Design Conference, Wingert (Reference 3) presented a paper that provided a more precise and commonly accepted definition:

"Workload is the ratio of the required performance time to the time available within the time constraints regulated by a mission."

Wingert's definition is very similar to our definition:

"Flight crew workload is the ratio of the summation of required crew-equipment performance time to the time available within the constraints regulated by a given flight or mission."

This can be expressed as follows:

$$FCW (\text{Percent}) = T_r / T_a \times 100$$

where

$$FCW (\text{Percent}) = \text{Flight Crew Workload in Percent}$$

$$T_r = \text{Time Required}$$

$$T_a = \text{Time Available}$$

This concept is most useful when comparing alternative means of accomplishing similar tasks, or providing similar information in the cockpit. It also facilitates the relating of tasks and task times to specific equipment so that efforts to reduce workload peaks can be directed to the proper equipment areas. Since our interest in workload is crew station design oriented, this concept is the one that seems to best support our goal of designing the most economic cockpits with acceptable and safe workloads and serves as a basis for a standard for comparisons.

FLIGHT CREW WORKLOAD ANALYSIS PROCEDURE SUMMARY

The procedure used in measuring flight crew workload is summarized in Figure 1. It starts with a typical flight plan developed to exercise all equipment of interest for this particular analysis. Using calculated or actual aircraft performance data and

the hypothesized environmental factors, a mission scenario is developed along with an event timeline. The time available segments are then created by the time difference between events or milestones.

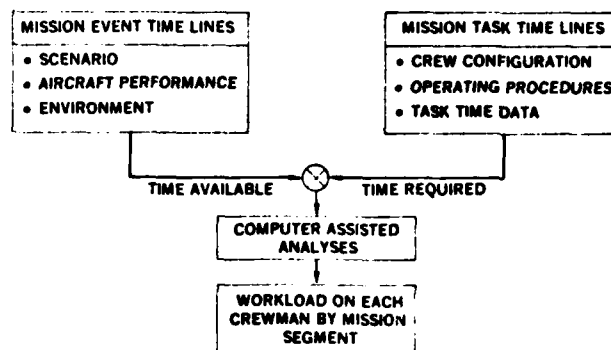


FIGURE 1. WORKLOAD ANALYSIS - METHODOLOGY

The operating procedures are established by coordinating inputs from experienced pilots using the published or proposed aircraft operating procedures for the proposed flight crew station configuration, and the equipment operating procedures proposed for the planned configuration. These procedures are refined and detail times developed by using a full-size design aid and published task time data to provide detailed task element time data. This establishes the time required for performing the various activities required for the flight.

The detailed flight sequences, time available data, and time required data are coded for acceptance by the computer program and entered into the computer for processing and analysis. The output from the computer consists of average and summary tabulations. These tabulations can be of total workload or the workload associated with various equipment and certain kinds of activities.

A separate routine referred to as the Select Option allows retrieval of task elements in accordance with specific codes associated with equipment, body actions, reach distances, responsible engineering groups, etc. Workloads are then computed for these groupings. By proper selection, it is then possible to determine which factors are significant in relation to overall workload or where the configuration could be improved most effectively to reduce workload peaks. This technique enables comparisons to be made on a numerical basis independent of personal opinion.

BASIS AND DESCRIPTION OF CALCULATIONS

The time available is based on a very detailed flight scenario that describes specific flight conditions, flight paths, and airspeeds. Using an event or milestone as the starting and ending points, the descent, approach, and landing has been divided into nineteen segments. Typical events or milestones are as follows: End Descent to 4000 Feet, Course Change to Heading 044, Start Speed Change 250-200 KIAS. Figure 2 depicts the final portion of the flight and shows the starting and ending points of some of the milestones. Figure 3 shows the relationship between altitude, speed, and heading for the last portion of the flight. The speed portion of this profile is developed using appropriate aircraft performance data, environmental factors, and speeds required on various segments of the flight. The headings, speeds, and altitudes are those required to follow the prescribed course specified by ATC in flying this approach and landing. The milestones are shown at the top portion of the chart which has time from

touchdown as the abscissa. The differential between the milestones forms the basis for calculating the Time Available, or T_A , for each discrete flight segment.

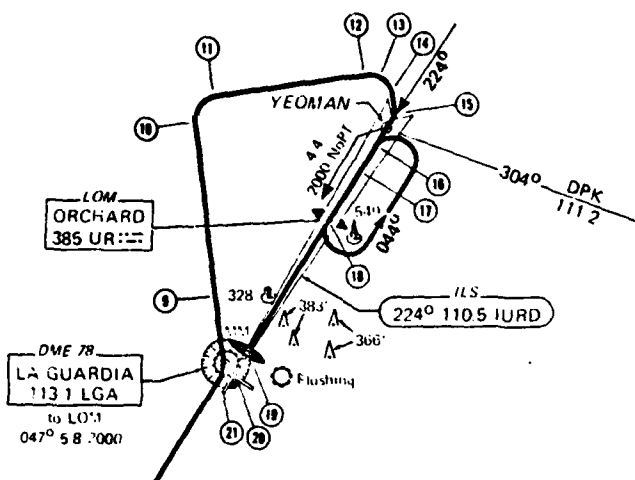


FIGURE 2. TYPICAL FLIGHT PATH MILESTONES

Developing the Time Required starts with the use of flight crew station drawings, proposed operating procedures for the aircraft, and operating procedures for the specific equipments proposed in the configuration under consideration. In close coordination with pilots experienced in similar aircraft, a very detailed description of the procedures required for flying each mission segment is developed. Figure 4 is an example of the worksheet used in

developing the procedures, time required, designating the crew member, and indicating the control or display involved. The time required for each action is calculated by using a standard data store that provides the times for actuating various types of controls and reading various types of instruments. (Reference 4)

Figure 5 is an example of this type of data. Reach times were developed using a full-size crew station mockup.

The procedures used reflect the operating techniques of one or two expert pilots who are experienced on similar aircraft. Other pilots might operate the aircraft slightly differently but in a comparative analysis, since operating procedures are changed only when required by equipment changes, such differences are not important to our measuring system. The times calculated from the published data stores have been standardized by testing a large number of subjects. This provides a solid base for use in identifying the changes in use times associated with change in the crew station configuration. It is this ability to identify change in use time as it affects overall workload that is most useful to crew station designers.

CODING DATA FOR THE COMPUTER

The data are organized in terms of missions, functions, tasks, and elements. Symbols and a brief description for each of these are used to facilitate both the computer processing of the data and the reading of computer printouts. Figure 6 simulates a computer printout for some of the elements in the landing phase. Some of the items are as follows:

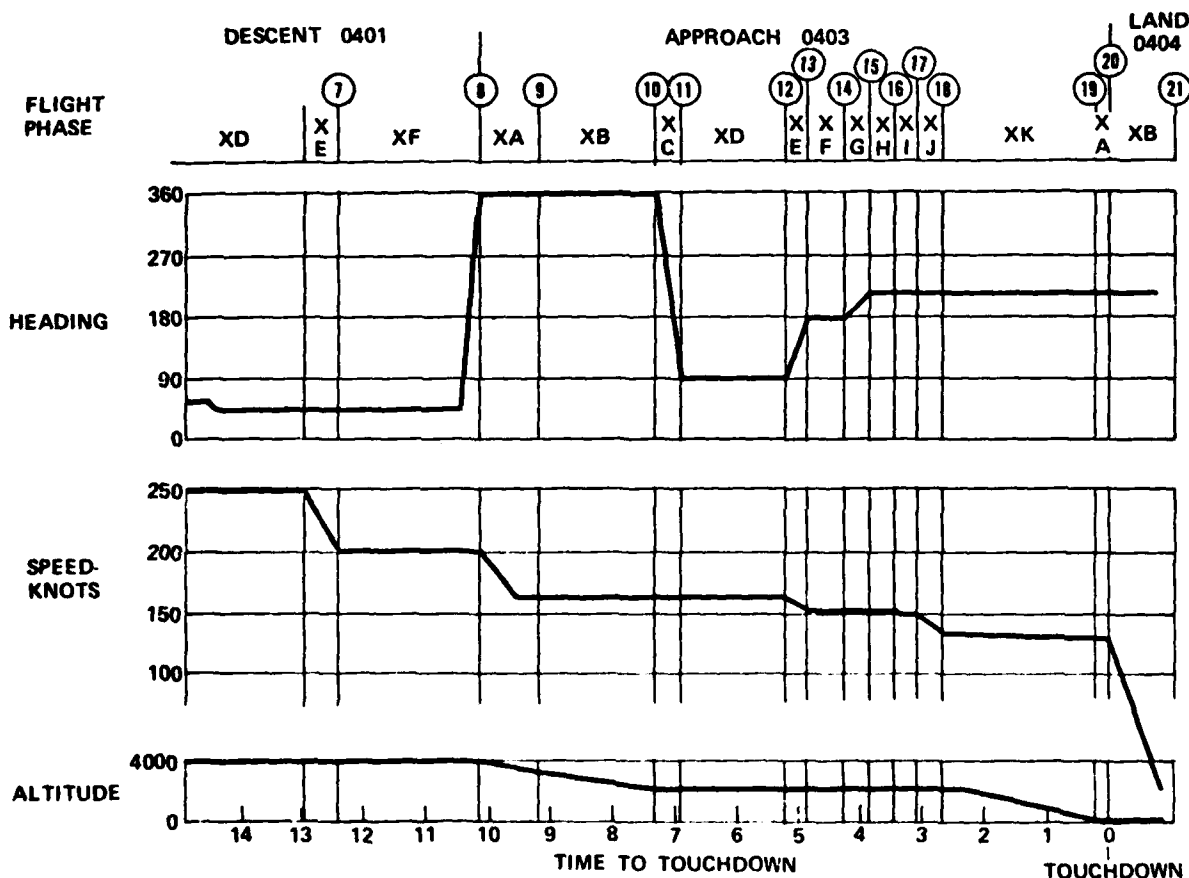


FIGURE 3. FLIGHT PROFILE SEGMENT

CHANGE NOTATION 00 PAGE INDEX ADDITION NO.

FLIGHT PHASE IDENTIFIER 0403 TITLE APPROACH

TASK IDENTIFIER BL TITLE SET FLAPS TO 50 DEGREES

NORMAL X	CONFIGURATION <u> </u>	CRITICALITY <u> </u>
CONTINGENCY	EQUIPMENT INTERFACE <u> </u>	DEFEFABILITY <u> </u>
DIL		

MISSION TIME HRS MIN SEC ELAPSED TIME HRS MIN SEC TOTAL TASK TIME REQUIRED SEC.

ELEMENT	DESCRIPTION	T _R	C	FO	CSD REFERENCE	REMARKS
01	CAPTAIN CALL OUT: FLAPS 50 DEGREES	1.0	X	X		
02	GRASP FLAP/SLAT HANDLE AND DEPRESS AND HOLD UNLOCK LEVER	1.4		X	CP-FL	
03	PULL FLAP CONTROL HANDLE TO 50-DEGREE DETENT POSITION	1.9		X	CP-FL	
04	RELEASE UNLOCK LEVER	0.6		X	CP-FL	
05	MONITOR FLAP POSITION INDICATOR UNTIL IT READS 50 DEGREES	8.0		X	PC-55	
06	FIRST OFFICER CALL OUT: FLAPS 50 DEGREES	1.0	X	X		
07						
08						

FIGURE 4. WORKSHEET USED TO MEASURE FLIGHT CREW WORKLOAD

INDEX OF ELECTRONIC EQUIPMENT OPERABILITY — DATA STORE
AMERICAN INSTITUTE FOR RESEARCH, REPORT NO. AIR-C43-1/62, 1962

SAMPLE DATA

CIRCULAR SCALES

BASE TIME - 0.50

TIME ADDED

1.03

0

0.03

1.50

1.50

0.25

0.25

0

1. SCALE DIAMETER

A. 1 INCH

B. 1.5 - 1.75 INCHES

C. 2.75 INCHES

2. SCALE STYLE

A. QUANTITATIVE READING (DETERMINE A SPECIFIC VALUE)

(1) MOVING POINTER

(2) MOVING SCALE

B. QUALITATIVE READING AND CHECKING (DETERMINE
WHETHER INDICATION IS WITHIN A CERTAIN RANGE)

(1) MOVING POINTER

(2) MOVING SCALE

(3) EITHER MOVING POINTER OR MOVING SCALE,
IF COLOR CODED

FIGURE 5. TASK/TIME ESTIMATES

1. 0403 XK99—END TIME

2. 000018 FC 000000

3. 0404 LAND 102374 FC

4. GS ELB U

5. 0404 XA ACQUIRE MM 0.5NM FROM THRESHOLD

6. 0404 AA00 ALTITUDE CALLOUT

7. 000018 FC 000000

8. 0404 AA01 MONITOR ALTIMETER TO READ 200 FT

9. 000000 FO 000300

10. E

11. 3-ATA34-13-01-120-410 C3

0404 AA02 CALL: 200 FEET

000000 FO 000050

VE

*1200 FEET

0404 AA03 RECVE: 200 FEET

000000 C 000050

12. V S

*1200 FEET

FIGURE 6. LANDING PHASE ELEMENTS (SIMULATED
COMPUTER PRINTOUT)

- Line 1 indicates the end of a function and task.
- Line 2 indicates the time the task ended.
- Line 3 indicates the phase of flight (Land).
- Line 5 indicates the milestone to be achieved.
- Line 6 indicates the task description.
- Line 7 indicates the time the task "XA" starts.
- Line 8 is the element description.
- Line 9 indicates which crew member is taking the action and the time required for this action.
- Line 10 indicates that the eyes are required for this task.
- Line 11 is the ATA number for the equipment involved in the element described.
- Line 12 is for another element and shows the Captain is involved in a communication task and is also performing an outside scan at the same time.

COMPUTERIZED DATA SUMMARIES

The computer program provides the capability to summarize and average the workload between designated milestones as related to all task elements or those selected on the basis of equipment or specialized task requirements. Figure 7 shows the flight crew workload summary for all task elements in a portion of the flight. The computer prints out the function symbol, task symbol, task description, and the percent workload for the Captain and the First Officer. The minus sign in front of the

WORKLOADS ARE FOR ALL TASK ELEMENTS

FUNC	TASK	TITLE	TIME		DURTN	PERCENT	WORKLOAD	
			H	M			C	FO
0401	XA	COMMENCE DESCENT TO 10,000 FT. REDUCE SPEED	00	20	18	200	-77.92	-72.75
0401	XB	END DESCENT AT 1500 FPM	00	18	18	3.00	-34.22	-28.72
0401	XC	END DESCENT TO 4000 FT	00	15	18	0.80	-4.17	-31.88
0401	XD	COURSE CHANGE TO HDG 044	00	14	30	1.60	-89.17	-82.29
0401	XE	START SPEED CHG 250 - 200 KIAS	00	12	54	0.50	-78.67	-63.67
0401	XF	END SPEED CHANGE	00	12	24	2.30	-27.61	-67.61
0402	XA	THIS PHASE NOT USED	00	10	06	-0.02	0.00	0.00

FIGURE 7. FLIGHT CREW WORKLOAD SUMMARY (SIMULATED COMPUTER PRINTOUT)

workload numbers is due to the technique of counting time back from the touchdown point.

Figure 8 shows a typical workload breakdown by equipment groupings and activities. It shows, for example, the high proportion of workload associated with the communications task in a high density area such as New York. The low value of workload required for outside scanning corresponds to the IFR conditions chosen to give high workload in other areas. The total level of workload, however, would allow outside scanning to be increased considerably, if needed. Outside scanning is also possible simultaneously with some of the other task elements listed. Figure 9 shows the detailed analysis that is possible when the workload elements are displayed for each task. This shows the major elements of the workload structure and how they change from task to task. Most of this 5-minute segment is with the aircraft on autopilot and the Captain takes over manually for the last 200 feet.

EQUIPMENT	FLIGHT PHASE WORKLOAD	
	DESCENT	
	CAPT	F.O.
TOTAL COMMUNICATIONS	19.5	32.9
VERBAL EXTERNAL	(10.3)	(16.4)
VERBAL INTERNAL	(8.9)	(8.9)
EQUIPMENT	(0.3)	(7.6)
FLIGHT INSTRUMENTS	10.0	3.0
NAVIGATION INSTRUMENTS	7.5	7.0
REACH	3.8	9.0
SYSTEM SCAN AND CHECKLIST	0.0	6.5
POWER PLANT	7.4	0.8
FLIGHT CONTROLS	0.0	0.0
AUTOFLIGHT	1.4	0.2
MISCELLANEOUS	3.2	1.4
NORMAL OUT SCAN (IFR APPROACH)	4.9	4.9
TOTAL	57.7	65.7

FIGURE 8. EXAMPLE OF FLIGHT CREW WORKLOAD BY EQUIPMENT OR ACTIVITY (PERCENT OF TIME AVAILABLE)

DATA USE IN CONFIGURATION EVALUATION

As stated previously, the primary purpose of this system is to provide data for use in comparative evaluation of alternative crew station designs. Any workload reduction must be evaluated in terms of the context within which this occurs and it seems senseless to increase the cost by automating a feature that saves work during low workload periods only. To illustrate how this

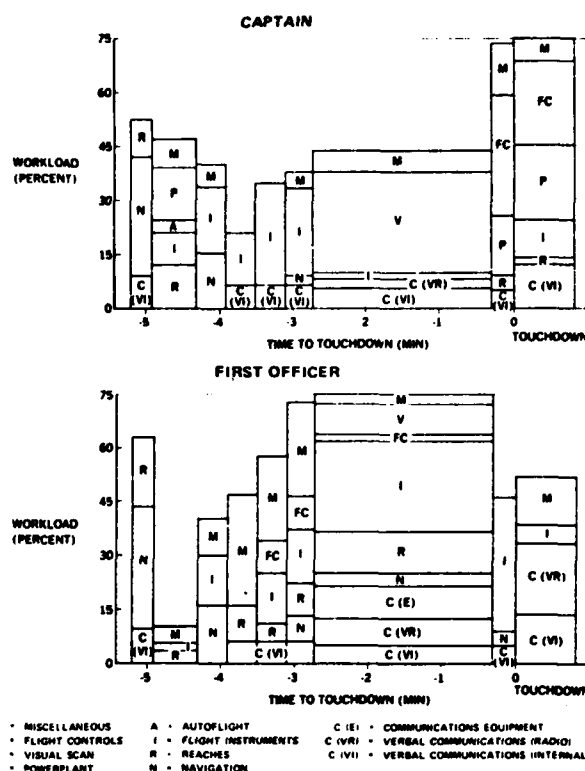


FIGURE 9. FLIGHT CREW WORKLOAD STRUCTURE ANALYSIS

analytic technique can be employed in configuration evaluation, the effect of an autothrottle system is analyzed.

The autothrottle system can be hypothesized as a completely automatic system that senses power requirements and continually adjusts the throttles accordingly, requiring no input or monitoring from the pilot. Figure 10 shows simulations of the computer printouts of workloads associated with manual operation of the throttles and monitoring of the EPR gauges. These values which are obtained by a select option computer sort can be subtracted from total workload figures for all the tasks and a plot made of the maximum savings possible. Figure 11 illustrates such a plot and shows that an autothrottle system may have significant potential for reducing the higher workloads. It makes a substantial reduction in workload for all but two of the higher workload periods. With a potential such as this to work with, various autothrottle systems can be hypothesized and the corresponding operating procedures derived, timed, coded, and fed into the computer for workload evaluation. Possible autothrottle system characteristics can then be traded off to arrive at the system that provides the most savings at the most critical times for an acceptable cost.

THROTTLE WORKLOAD							
SELECT OPTION TAKEN							
CARD TYPE 8, FIELD 124, FIELD CONTENT 76-11							
FUNC	TASK	TITLE	TIME H M S	DURTN MIN	PERCENT C	WORKLOAD FO	
0403	XA	MANEUVER FOR APPROACH	00 10 06	1.00	7.00	0.00	
0403	XB	END DESCENT TO 3000 FEET	00 09 06	1.90	11.05	0.00	
0403	XF	END HEADING CHANGE	00 04 54	0.60	17.50	0.00	
0404	XA	ACQUIRE MM 05 N MI FROM THRESHOLD	00 00 18	0.28	14.71	0.00	
EPR WORKLOAD							
SELECT OPTION TAKEN							
CARD TYPE 8, FIELD 126, FIELD CONTENT PC-47R							
FUNC	TASK	TITLE	TIME H M S	DURTN MIN	PERCENT C	WORKLOAD FO	
0403	XB	END DESCENT TO 3000 FEET	00 09 06	1.90	2.24	0.00	
0403	XF	END HEADING CHANGE	00 04 54	0.60	2.08	0.00	
0404	XB	ROLLOUT	00 00 01	0.78	7.66	0.00	

FIGURE 10. THROTTLE MANIPULATION AND EPR GAUGE MONITORING WORKLOAD

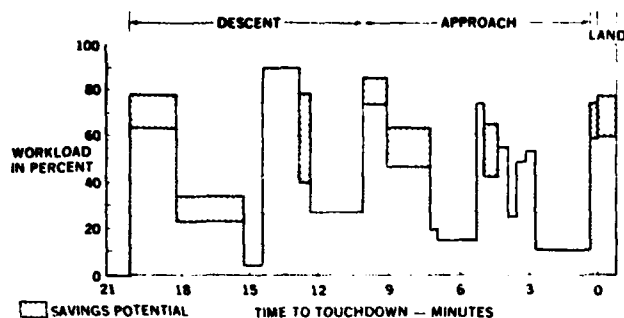


FIGURE 11. SCOPING POTENTIAL AUTOTHRUSTLE SYSTEM SAVINGS FOR CAPTAIN

Another example illustrating the utilization of these procedures involves the consideration of a boom or hand-held microphone. Most pilots are well aware of the substantial workload reduction associated with using a boom or oxygen mask microphone compared with a hand-held microphone. To determine the effect of this change, a computer run was prepared that selected out all the times associated with picking up a mike, bringing it to a talking position, and returning it to the stored position. The results are shown in Figure 12. These are in agreement with the commonly held opinion that a boom mike does help with some of the higher workload tasks for the First Officer, and in addition, the numerical results of this evaluation indicate the significant effect of this change. It is this quantification of improvements, with objectively derived data, that is the key contribution of this system. For any aircraft operator that has a First Officer (Copilot) currently using a hand mike and complaining of overwork, this is probably the cheapest way to reduce his workload.

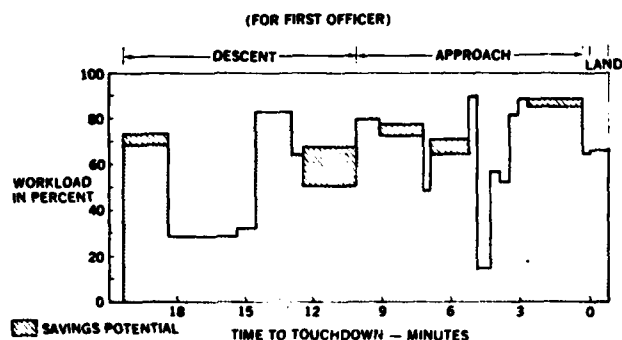


FIGURE 12. BOOM MICROPHONE USE SAVINGS POTENTIAL

CAPABILITY EXPANSION

There are several ways in which the capability of the Cockpit Evaluation and Design analysis System can be expanded and made more useful. At the present time the development of new scenarios and their attendant milestone times is a very time consuming and laborious task. The full evaluation of a multipurpose or high capability aircraft would require several different scenarios, each with the aircraft configured differently in terms of the payload. The sequence of actions within the mission, as well as many actions themselves, would be different. An automated capability to develop these scenarios and times would greatly increase the usefulness of this technique.

Another technique for speeding up crew station evaluations would be to develop a library of operating procedures associated

with various crew station equipment that might be chosen for installation. These operating procedures could then be retrieved from the computerized library and developed as required for the scenario.

The concept of Time Required for flight crew workload evaluation used in the computations is shown in Figure 13. This can be conceived of as a vertical slice of workload as it could exist during some short period of time. Most of these elements can be quantified for any given situation. While most of our work has been with the Normal Procedures Demands, one example of Abnormal Flight Environment Demands has been quantified and the results are shown in Figure 14. This chart shows the additional increment of workload that is added when a VFR, day flight is changed into a night, IFR flight with darkness, clouds, icing, and rain to contend with.

TIME REQUIRED	SAFETY ASSURANCE REQUIREMENTS	SELF-CHECK AND CROSS-CHECK ALLOWANCE
		EMERGENCY PROCEDURE DEMANDS
		ABNORMAL FLIGHT ENVIRONMENT DEMANDS
		ABNORMAL PROCEDURES DEMANDS
		DISPATCH INOPERATIVE DEMANDS
		NORMAL PROCEDURES DEMANDS
		MINIMUM ACTIVITY FOR CREW ALERTNESS

FIGURE 13. TIME REQUIRED ELEMENTS OF FLIGHT CREW WORKLOAD

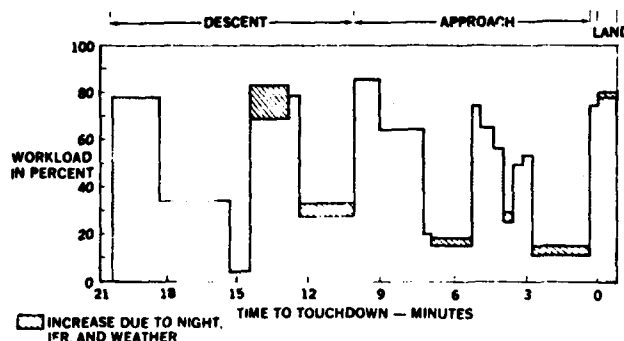


FIGURE 14. INCREASED WORKLOAD DURING NIGHT, IFR, AND WEATHER CONDITIONS FOR CAPTAIN

The Cockpit Evaluation and Design Analysis System is not developed to the point where all the time demands of the flight crew workload elements as depicted in Figure 13 can be quantified. When they are, it will provide a significant increase in the flexibility of this system and its usefulness to designers who are directing their efforts toward providing safe and economical crew station configurations. Experienced pilots are all too familiar with situations where the time demands of the various elements listed in Figure 13 sum to a point where inadequate time is available for necessary self-check and cross-check activity. If the time demands of all the various workload elements can be quantified, considered, and traded off during the design process, then crew station designers will have their attention directed to those items of equipment that must be improved to provide a safe and economical crew station arrangement that is viable under most adverse conditions.

ADDITIONAL APPLICATIONS

This system also lends itself to development for use in crew sizing studies for particular military missions. The workload measuring technique could provide key information, including the following:

1. The effect on aircraft overall configuration and the equipment needed for a particular mission with various crew configurations.
2. Definition of tasks, task times, and the task assignments associated with various phases of the mission with various types of procedures that could be used to accomplish it.
3. Analysis of workload for each crewman as a function of the airplane/crew configuration and mission phase.
4. Analysis of the resulting differences in the nonrecurring and recurring portions of acquisition and lifecycle cost differences to achieve the most cost effective compromise.

CONCLUSIONS

The cockpit evaluation, design, and analysis system described in this paper is being used by the Douglas Aircraft Company in crew station design studies. It provides an effective method for objective analysis of proposed cockpits early in the design stage. The analytical methods developed are also sufficiently flexible to

handle unforeseen requirements as crew station designers understand its potential and request additional types of information. While the uses at this time have been concerned primarily with the cockpit crew station, it can be used for mission crew stations elsewhere and it can be utilized as a crew sizing technique.

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