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Flight Deck Automation: Promises and Realities

Proceedings of a
NASA/FAA/Industry Workshop
held at Carmel Valley, California
August 1 - 4, 1988

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Flight Deck Automation: Promises and Realities

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PREFACE

Issues of flight deck automation are multi-faceted and complex. The rapid introduction of advanced computer based technology onto the flight deck of transport category aircraft has had considerable impact on both aircraft operations and the flight crew. As part of NASA's responsibility to facilitate an active exchange of ideas and information among members of the aviation community, and since the timing appeared appropriate for a discussion of the effects of these changes on the roles of the crew and the automation, a NASA/FAA/Industry workshop devoted to flight deck automation was organized by the Aerospace Human Factors Research Division of NASA-Ames Research Center.

The workshop was held at the Carmel Valley Inn in Carmel Valley, California, August 1-4, 1988. Participants were invited from industry and government organizations responsible for design, certification, operation, and accident investigation of transport category, automated aircraft. Attendees included representatives from airframe manufacturers, air carriers, the NTSB, the FAA, NASA and the university community.

The workshop took a broad systems level perspective and discussed the design, training and procedural aspects of flight deck automation, as well as the crew's ability to interact and perform effectively with the new technology.

The goals of the workshop were to clarify the implications of automation, both positive and negative, and to identify issues regarding the design, training and operational use of flight deck automation. Participants with operational, training, or design experience were crucial to achieving these goals.

A small preliminary, NASA workshop attended by NASA-Ames research staff and three human factors specialists was held to prepare for the industry-wide workshop. Thereafter, a source document on automation philosophies was prepared, and that report is included in the appendix. It is intended as an introduction to the concepts and ideas regarding flight deck automation which were discussed at this workshop.

The remainder of this report presents the final results of the August workshop. The ideas and concepts in this document were developed by the workshop participants and written primarily by the NASA-Ames research staff. Since the workshop was small and informal, this report is not a verbatim transcript of the proceedings. Instead, the findings have been synthesized, where necessary, into an aggregated format and individuals and organizations have occasionally been de-identified. This format was chosen to facilitate a free exchange of information at the workshop.

The workshop consisted of four major sessions:

Introductory panels: Informal presentations by industry and government representatives on the design, operation, and certification of the automated cockpit.

Formal papers: Formal presentations by members of the aviation community pertaining to automation in an operational context.

Workshop group discussions: Six working groups were convened to discuss specific aspects of automation. These were:

- Automation and Air-Ground Communication
- Crew Coordination
- Understanding Automated Systems
- Training for Advanced Technology Aircraft
- Error Management
- Design Philosophies and Certification Issues

Summary session: Summary and concluding remarks by the chair and other participants.

FLIGHT DECK AUTOMATION:
PROMISES AND REALITIES

INTRODUCTION

Susan D. Norman
Chair

In developing the format and content for this workshop, considerable attention and time were given to the relationship between the aircraft design, certification criteria, operational procedures and training for transport category aircraft. Extensive discussions with aviation and human factors specialists were held at NASA-Ames, NASA-Langley and at various group meetings, including the ATA task force on human factors. The chair is much indebted to these people and discussions with them concerning the technical content and format of the workshop.

In these discussions, it became clear that one important aspect of cockpit automation was the increasingly complex interaction between the processes of design, training, operations, and certification of the aircraft. The complexity of the new technology necessitated a clear understanding of the effect these processes have on one another in an operational setting. This was particularly important because, in time constrained situations, automated systems are often not as flexible as their human counterparts nor are their designs normally able to function as effectively as a human in nonstandard conditions.

With this in mind, the panels and working groups were structured to explore the interdisciplinary, system level aspects of the automated cockpit. This workshop was to be a unique opportunity to understand the implications of how one element of the process impacted another; for example, how the implementation of a design or philosophy could impact the operational procedures or the interface with ATC.

In preliminary discussions, it was also clear that the role of the pilot and crew was a key factor. Had it changed and if so, how? Was any apparent change moving in an appropriate direction? As a humorous exaggeration of the potential for a new role for the pilot, the question was asked if participants knew what the air transport crew of the 21st Century would look like? The answer was that the crew would be composed of two members, a pilot and a dog. The pilot was responsible for feeding and caring for the dog, and the dog was there to bite the pilot if he touched anything.

Although certainly not intended to be realistic, this joke drives home the point about the potential role of the flight crew in future aircraft. Of the many unanswered questions presented to this workshop, those regarding the role of the crew were the most difficult. Is the potential for change in the role of the crew a valid concern?" and, if so, "Is this the direction the industry, as a whole, wishes to go?"

Finally, it was intended that the workshop focus on operational realism, because real, versus perceived, problems and benefits need to be specified. Although there was considerable discussion of the theoretical aspects of cockpit automation, including philosophies of automation, the workshop was not intended to be theoretical in nature. It is important to understand and assess the existing situation before any changes, future research programs or philosophies are developed. A view toward the future is important, but a critical understanding of the current situation must form the basis for any discussions of the future.

PANEL DISCUSSIONS

Panel
CURRENT FLIGHT DECK AUTOMATION: AIRFRAME MANUFACTURING AND FAA CERTIFICATION

Prepared by Susan Norman and Kathy Abbott

Moderator: Sam Morello, NASA-Langley Research Center
Members: Harty Stoll, Boeing Commercial Airplane Company
John Miller, Douglas Aircraft Company
Don Armstrong, FAA Aircraft Certification

INTRODUCTION

The new generation of automated aircraft has increasingly used technology on the flight deck to enhance factors such as safety of flight and economic performance. The process of developing a new aircraft begins with the design where many fundamental and irrevocable decisions are made. Therefore, a discussion of automated aircraft technology should begin with the philosophy of design.

The panel members were asked to describe, based on their extensive experience, the current philosophy of automation and to cite examples which illustrate how this philosophy has been implemented. The interrelationship of the certification process and its impact on the design were also discussed on this panel, since the FAA regulations must form the basis for an overall, system wide check on the performance of the aircraft in an operational environment.

The major points from this session have been summarized and reorganized by topic to capture the essence of the presentations made by the panel members. The design and certification issues are discussed separately.

DESIGN IN AN AUTOMATED ENVIRONMENT

The manufacturers presented their perspectives with examples from the most recently designed aircraft. The figures were presented by Mr. Harty Stoll of the Boeing Commercial Airplane Company.

Benefits of Automation

It is important to state that automation has been a clear and continued benefit in terms of safety of flight. There is no question that the advances made in the reduction of the accident rate associated with human error have occurred to some extent because of the introduction of automation onto the flight deck. But, because the workshop focussed on what can be done to improve safety of flight, most of the discussions centered on issues and problems as opposed to benefits. This is not intended to be a reflection on the technology itself.

WORLDWIDE 737 OPERATORS DECEMBER 31, 1987

OVER 200 OPERATORS TWO PILOT CREW (1,450 AIRPLANES) 25 MILLION FLIGHT HOURS

ABU DHABI	BAHAMASAIR	FEDERAL EXPRESS	MONARCH AIRLINES	SPANTAX
AER LINGUS	BAVARIA	FLIGHTPATH LTD	NATIONAL AIRLINES	STAR JET CORP.
AEROLINEAS ARG	BEIJING	FRONTIER	NEW YORK AIRLINES	SUDAN AIRWAYS
AERO TOURS	BRAATHENS	GUANGZHOU REGION	NIGER-GOVT	SUN WORLD
AIR ALGERIE	BRANIFF	GULF AIR	NIGERIA AIRWAYS	SUNLAND AIRLINES
AIR ATLANTA	BRAZIL	GUYANA AIRWAYS	NISSHO-IWAI CO.	SURINAM AIRWAYS
AIR BELGIUM	BRITANNIA	HAPAG-LLOYD	NOGA	TACA INTL AIRLINES
AIR BERLIN	BRIT AIRTOURS	HISPANIA	NORDAIR	TAME-ECUADOR
AIR CALIFORNIA	BRITISH AIRWAYS	IBERIA	NORDSTRESS	TAP/AIR PORTUGAL
AIR COMORES	BRITISH MIDLAND	ILG TRAVEL	ORION AIRWAYS	TEXAS AIR
AIR DJIBOUTI	BUSY BEE	INDIAN AIR FORCE	PACIFIC EXPRESS	THAI AIR FORCE
AIR EUROPE	CAAC	INDIAN AIRLINES	PACIFIC SW	THAI AIRWAYS
AIR FRANCE	CAMEROON AIR	INDONESIA GOVT	PACIFIC WESTERN	TRANS AIR
AIR FLORIDA	CANADIAN AIRLINES	INTER EUROPEAN	PAKISTAN INTL	TRANS EUROPEAN
AIR GABON	CAYMAN AIRWAYS	IRAN-GOVT	PAN AM	TRANSAVIA
AIR GUINEE	CONTINENTAL	IRANAIR	PEOPLE EXPRESS	TRANSBRASIL
AIR HAITI	CHALLENGE	IRAQI AIRWAYS	PETROLAIR	TRANSPACIFIC
AIR LANKA	CHINA AIRLINES	ISRAEL INLAND	PIEDMONT	TUNIS AIR
AIR LIBERIA	CONDOR	ITEL AIR	PLUNA	UNIT AR EM-GOVT
AIR MADAGASCAR	COPA-PANAMA	JAT	POLYNESIAN AIR	UNITED AIRLINES
AIR MALTA	CORSE AIR	KABO	PRESIDENTIAL AIR	UNITED AVIATION
AIR MALI	CP AIR	KOREAN AIR FORCE	QUEBECAIR	UNITED TECH
AIR NAURU	CRUZEIRO	KUWAIT AIRWAYS	ROTTERDAM AIR	UNIVERSAIR
AIR NEW ZEALAND	DAN-AIR LONDON	LAUDA AIR	ROYAL AIR MAROC	US AIR FORCE
AIR TANZANIA	DELTA AIRLINES	LINHAS	ROYAL BRUNEI AIR	US GOVT-NASA
AIR ZAIRE	DOME PETROLEUM	LINA-CONGO	ROYAL DUTCH AIR	USAIR, INC.
AIR ZIMBABWE	DRAGON AIR	LADECO	ROYAL SWAZI	VARIG AIRLINES
AIRWAYS INTL	EAGLE AIR	LAN-CHILE	SABENA	VASP
ALASKA AIRLINES	EG&G-LAS VEGAS	LUFTHANSA	SAHSA	VENEZUELA-GOVT
ALL NIPPON	EGYPT-GOVT	LUXAIR	SAT	VIVA
ALOHA AIRLINES	EGYPTAIR	MAERSK AIR	SAUDI ARAB GOVT	WESTERN AIR
AMERICAN AIRLINES	EL AL	MALAYSIA AIRLINES	SAUDIA	WIEN AIR ALASKA
AMERICA WEST	ELDORADO	MARITIME INV CO	SAVAR	XIAMEN
ANGOLA AIRLINES	EMIRATES AIRLINES	MARK AIR	SHARJAH-GOVT	YEMEN AIRWAYS
ANSETT AIRLINES	ETHIOPIAN	MECOM CO	SINGAPORE AIR	YUNNAN
ARAB INTL AIRLINES	EURALAIR	MEXICO-GOVT	SKYBUS INC	ZAMBIA AIRWAYS
ARAMCO	EUROPE AERO	MEY AIR	SOBELAIR	
AUSTRALIAN A.F.	EXECUTIVE AIR	MIDLAND MONTAGU	SOUTH AFRICAN	
AUSTRIAN AIRLINES	FAR EASTERN AT	MIDWAY AIR	SOUTHWEST-JAPAN	
AVIANCA	FAUCETT	MIDWAY EXPRESS	SOUTHWEST-US	

THREE CREW (ONE AIRLINE-AIR FRANCE)

Figure 1

Although it is difficult to quantify the actual level of improvement in the accident rate associated with human error, there are some statistics which indicate this general trend. First, it is important to recognize the large number of flight operations and departures in today's air transport system. Figure 1 lists the worldwide Boeing 737 operators as of December, 1987. It shows that there are about 200 air carriers and 25 million flight hours per year.

Second, the accident rate for crew caused accidents has been decreasing. Figure 2 shows the data as a function of aircraft and its associated level of automation. Although there are many factors which impact these data, it is clear that the overall accident rate has not increased, and automation has been a factor in this reduction.

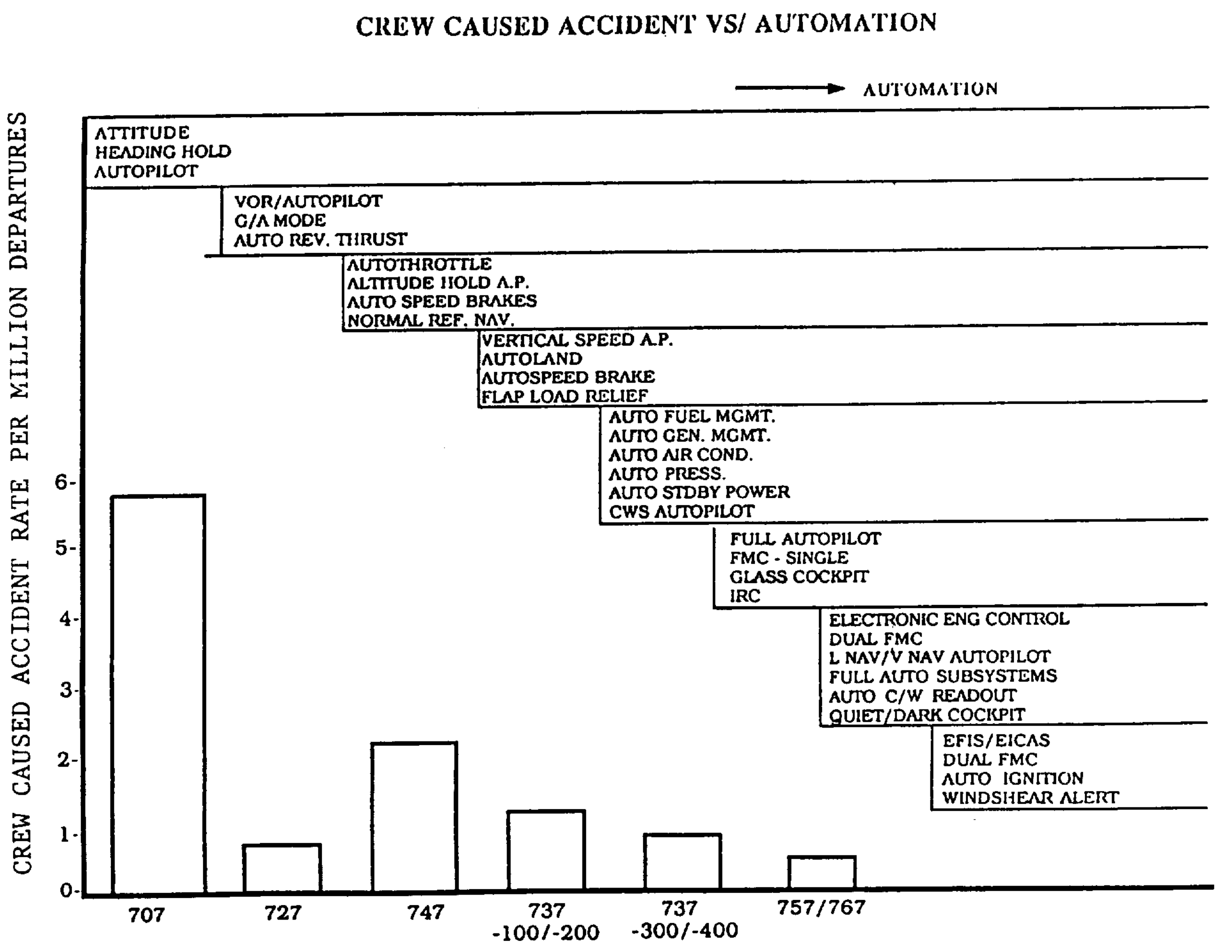


Figure 2

The Development Process

The design process for developing a new aircraft is complex. Improvements in the design to reduce the potential for human error are an active part of the design process. Manufacturers consult flight test pilots and operational carriers to determine their needs and assess the impact of technology.

Boeing has a formal Flight Deck Design Committee which reviews accident data and makes specific recommendations regarding the design of the flight deck. These new design options are available only because of the new automated or computerized technology which exists today. Examples of the accident related causes and associated design improvements which were incorporated into the Boeing 767/757 design are given in Figure 3.

In addition to examining accident statistics, Boeing also reviews major problems and identifies their associated subproblems. A recommendation is then made for an improvement in the design. As examples, Figure 4 lists the major recommendations for the 747-400/737-300.

Boeing Flight Deck Design Committee

Examples of Accident Data Reviewed
Subsystem Management Accidents—Worldwide Air Carriers
1968-1980

Accident Related Cause	767/757 Design Improvements
• Crew omitted pitot heat	• Auto on with engine start
• Wrong position of standby power switch	• Automated standby and essential power
• Flight engineer and captain conducted unauthorized troubleshooting	• Simplified systems; delete maintenance functions
• Electrical power switching not coordinated with pilots	• Auto switching and load shedding—no crew action required
• Flight engineer shut off ground proximity warning system	• Shut off on forward panel in full view of both pilots
• Faulty fuel management	• Auto fuel management with alert for low fuel, wrong configuration, and imbalance
• No leading edge flaps on takeoff with digital computer	• Improved takeoff warning
• Confusion over correct spoiler position	• Dual electric spoiler control
• Crewman did not follow pilot's instruction	• Full-time caution and warning system
• Mismanaged cabin pressure	• Dual auto system with auto switchover

Figure 3

Boeing Flight Deck Development Committee
Major Problems Identified

Problem	Sub-Problem	Recommendation
1) Lack of timely aircraft position information	• Approach information difficult to read	• MAP display • FMS
	• Exact airplane positions not always known—high workload	• INS-type information
	• Difficult to plan ahead	• FMS, MAP plan mode
2) Engine control & monitoring caused high workload	• Difficult to rapidly set desired thrust	• Electronic engine control
	• Large number of throttle adjustments	
	• Lack of alerting for out-of-tolerance condition	• Alerting means included with engine instruments
3) Inadequate caution and warning system	• Excessive aural and nuisance alerts	• Quiet, dark flight deck
	• Lack of standard color usage	• Standardize colors
	• Alerts not centralized or categorized	• Central alert with improved logic—simplified systems
4) System management causes high workload and errors	• Increase of hardware and functions of systems increases error	• Simplify systems • Simplify panel hardware
	• Monitoring of out-of-tolerance conditions increases workload	• Add redundancy and automation so no immediate crew action required
	• Increase procedures	
5) Inadequate design evaluation methods	• No means to evaluate design before they are integrated in cockpit	• Develop new computerized workload techniques
6) Display reliability	• Single systems limit error detection	• Digital computers • CRT displays
	• Panel temperature reduces reliability	• Liquid crystal display • Reduce LRUs • New concept for equipment cooling

Figure 4

7) Irritation and crew fatigue items	• Cockpit noise • Air conditioning and circulation • Eye fatigue • Seat comfort • Inadequate stowage	• New equipment and requirements
	• Instruments and lighted pushbuttons too hot	• New pushbutton concept required
8) Inadequate or uneven illumination	• New displays make lighting balance more difficult	• Automatic dimming controls
9) Poor readability of displays	• Improved contrast • Visual angle too small	• New equipment to higher standards
10) Inadequate landing vision and vision for collision avoidance.	• Low minimums require better down vision	
	• Windows not designed to collision avoidance	• New window design criteria

Figure 4 (continued)

Design Philosophies

The Boeing design philosophy is best characterized by an emphasis on simplicity first, then redundancy, and last automation (Figure 5).

EFFECTIVE SYSTEMS DESIGN:

Simplicity

Redundancy

Automation

Figure 5

As examples of the implementation of this philosophy, the design of the Boeing 747-400 has centralized and reduced the crew alerting system so that it is simpler for the crew to determine what is happening. Another example is the fuel system on the 747-400. The original design specified 5 fuel tanks per wing because of structural considerations in the wing. But, from an operational standpoint, this design needed a total of 10 boost pumps (two per tank). The resulting fuel crossfeed procedures were determined to be overly complex and the design team elected to simplify the overall system by implementing a baffled tank structure. The resulting system had only 3 tanks per wing and used some automation in the middle tank to assist in the reduction of operational complexity. This illustrates the importance of first designing to simplify which may, in turn, reduce the need to automate.

The Boeing automation philosophy is summarized in Figure 6. Automation does have a vital role in aircraft safety design. This is best exemplified in the automation of engine controls. With the introduction of appropriate automation, the engines can now be fire-walled simply by moving the throttles forward and it is not necessary to adjust any other controls.

Another important issue for the design of state-of-the-art aircraft is the pilot role. John Miller of Douglas indicated that the MD-11 has been designed with the criteria that any irrevocable action, such as engine shutdown, must have a manual pilot action.

Automation Philosophy

- **Simplified/Minimized Crew Procedures for Subsystem Operation**
  - **Reduces random and systematic error**
  - **Increases time for primary pilot functions**
  - **Prevents requiring any immediate crew action**
  - **Reduces subsystem mismanagement accidents**
  - **Centralizes crew alerting for error reduction**
  - **Allows "fire walling" engine controls**
  - **Allows two member crew operation**
- **Improved Navigation Information**
  - **More exact airplane position indication (MAP)**
  - **Reduces fuel usage**
  - **Higher reliability and improves accuracy**
  - **Reduces crew error**
  - **Reduces workload, allows more pre-planning**
- **Improved guidance and control**
  - **Reduces workload**
  - **Allows low minimum operation**
  - **Allows manual, semi-automatic or automatic pilot flight**
  - **Increases precise guidance information**

Figure 6

Both manufacturers' design philosophies included the concept that the pilot should primarily be responsible for flying the aircraft. A minimum of crew procedures facilitated this task. For example, during the MD-11 design process, procedures were minimized where possible, particularly when the procedure could be pre-specified (i.e., there were no options or choices). For example, the MD-11 has six CRTs, and in the case of a failure of one, there is a specific, recommended reconfiguration for the five remaining displays; similarly with 2 failures, etc. Instead of making this reconfiguration process a procedure, the decision was made to automate it, because the reconfiguration could be predetermined. The crew would then be able to focus their attention on flying the aircraft, instead of referring to a procedural manual to reconfigure the CRT displays.

Regarding function allocation, both manufacturers indicated that the subsystem management area was most amenable to automation because of the highly proceduralized nature of the task. The Boeing philosophy of allocation is illustrated in Figure 7. Those tasks associated with the guidance and control of the aircraft have remained with the most direct crew involvement because these tasks are dynamic and critical.

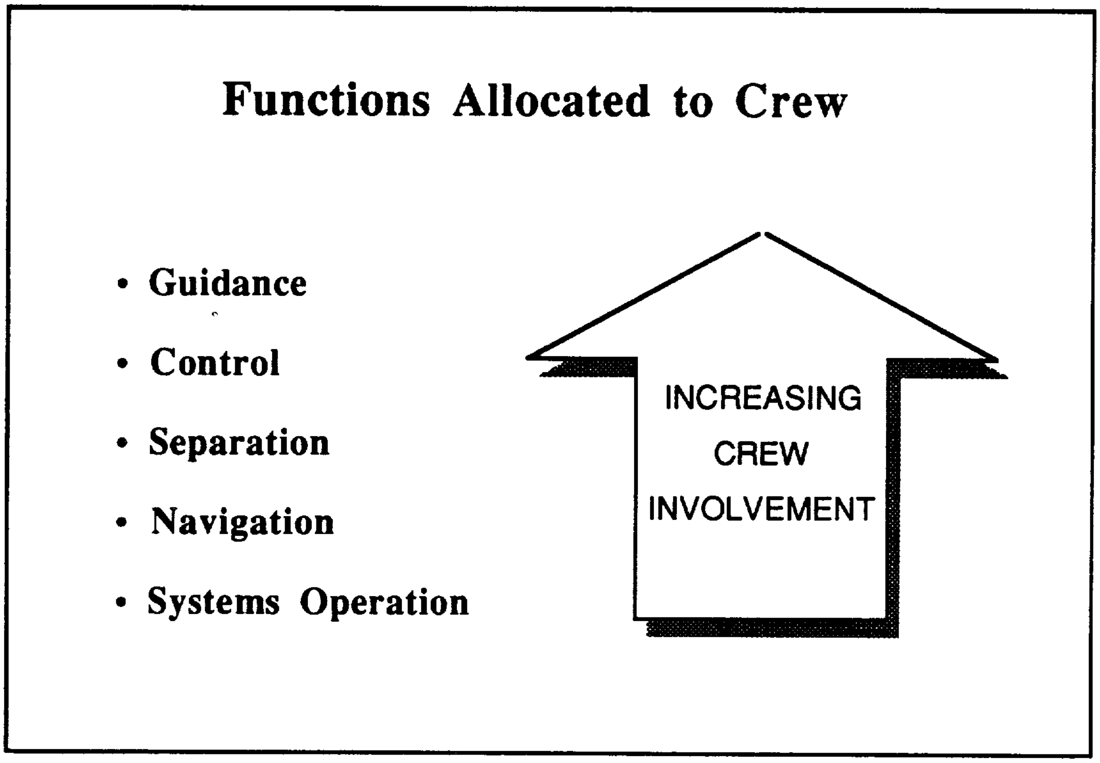


Figure 7

Lessons Learned

With the introduction of systems such as the CDU, a lot of heads-down time resulted, especially at first. During the original design, such systems were not intended to be used during periods of frequent ATC changes, particularly in the terminal area. However, a great deal of emphasis was placed on the FMC/CDU during the certification because it was a new system. It was also emphasized during training, which may have caused an over-emphasis during check rides. The result was that pilots may have felt obligated to use it in the terminal area even though this was not the original design intent.

CERTIFICATION IN AN AUTOMATED ENVIRONMENT

A brief overview of the FAA certification process was presented by Don Armstrong. There are three basic phases: setting standards, substantiating designs by analyses and laboratory tests, and flight tests.

With respect to the standards, the rules attempt to be as objective as possible. For automatic digital systems, there are three basic requirements:

1) The system must perform the intended function.

2) The system must meet all applicable requirements; e.g., specific rules governing electrical loads, circuit protection, electromagnetic interference, flammability, etc.

3) The system must interface properly with all other systems, and with the crew.

However, new concepts often do not have suitable standards, and it becomes necessary to work with the applicant to determine appropriate certification criteria. In fact, the rules are inherently two to three aircraft generations behind the state of the art of the technology to which they apply.

The next aspect of certification involves design substantiation, which involves three aspects for automatic and/or digital systems: software testing, hardware testing and the integrated system level tests. Software is categorized into three classes according to the importance or criticality of failures: critical, essential, and non-essential. Software which is critical to continued safe flight and landing (where failures can have potentially catastrophic results) is classified as critical. The most rigorous analyses and tests are conducted to assure that such failures will be improbable or extremely improbable. Equipment whose failures result in little effect on continued safe flight is classed non-essential, and their failure rates can therefore be relatively high.

Hardware is given the usual "shake and bake" testing which has been the industry standard for years. The hardware and software are then tested in an integrated manner to assure that the components function as expected.

The final phase of the certification process is flight testing. Every major sequence of events (changes from one mode of operation to another) is included in the flight scenarios. However, since it is not possible to evaluate every conceivable situation or series of mode changes, the flight tests must inevitably be spot checks of families of logical sequences. Cockpit layouts, including labeling, lighting, and annunciation under normal and abnormal conditions, are evaluated. Finally, workload effects are assessed, but, in the end, the final flight test results represent the consensus of the subjective evaluations of the flight test pilots.

This workshop offered an opportunity to air some concerns regarding the current certification process in the hope that a broader perspective could be gained and that certain issues might be further clarified. Some of these issues are:

1) The current rules do not have any comprehensive human factors requirements; instead, the subjective evaluation of the flight test pilot determines certifiability. This is worrisome not because of the subjective evaluation itself, but because the design engineers have made critical design decisions long before the flight tests occur, and changes are routinely resisted due to cost and schedule impacts. In the absence of rules which incorporate human factors criteria, the question is whether these design decisions adequately reflect the concerns of the FAA test pilots and the line pilots they try to represent.

2) Although this is difficult to admit, modifications by a manufacturer to previously approved models, or installations of new systems to existing aircraft by modifiers resulting in STCs*, are not usually rigorously evaluated for human performance criteria such as crew workload. This is becoming an increasingly important issue because of the increased complexity of these modifications, particularly in the business jets.

3) It is difficult to focus on standardization since the dominant manufacturing strategy is to meet the customer's requirements. For example, it is possible to present information using different colors, signals on or off, aural messages which are loud or soft, high numbers up or down, data which are always present or sometimes inhibited, etc., etc. The situation is further complicated by the fact that the industry has diverse opinions. These opinions even differ within the same manufacturer, let alone between the various FAA offices, and even perhaps between the test pilots within a single office. There are many cries for standardization, but the FAA is understandably reluctant to impose its will because to do so not only dictates design, but may also inhibit innovation.

*Supplemental Type Certificates

4) Flight test pilots of necessity make individual subjective assessments. The primary concern here is that the lack of standards for such assessments may not allow predictable results to be achieved among the small universe of pilots in the several FAA offices.

5) There is a critical need for a definitive, widely accepted training course in human factors for FAA test pilots.

In conclusion, a quote from St. Paul in his Epistle to the Romans was cited: "You wish to have no fear of the authorities? Then continue to do right and you will have their approval, for they are God's agents working for your good."

Panel
REALITIES OF OPERATING AUTOMATED AIRCRAFT: AIR CARRIERS AND FAA-AIRCRAFT EVALUATION

Prepared by Susan Norman and George Steinmetz

Moderator: Earl Wiener, University of Miami
Members: Al Ogden, United Airlines
Jack Wisely, TWA
Stu Grieve, Britannia Airways, Ltd.
Rod Lalley, FAA-Aircraft Evaluation

INTRODUCTION

The previous panel discussed the design and certification processes. In the real operational world, however, unforeseen events occur which can cause problems even with the most thoroughly planned and carefully engineered systems. With this reality in mind, the representatives of the air carriers and an FAA aircraft operational evaluation organization were asked to discuss issues associated with the introduction of the new generation of automated aircraft and to cite examples, based on their operational experience, which illustrated these issues.

This paper summarizes the panel presentations and discussions, but is not intended to be a consensus of the panel members. It is organized by major topics which may overlap in content because automation, itself, is a highly complex subject. Since most of the important points made during the panel discussion are related to the technology and not the carrier or manufacturer, references to specific air carriers and manufacturers have, for the most part, been deleted.

LESSONS LEARNED FROM OPERATIONAL INCIDENTS

Benefits

The benefits associated with autoflight are substantial and this fact should not be lost even though most of the panel discussion, and hence the report, concerned how to improve our use of automation. As an example, the Boeing 767 was one of the first aircraft to employ substantial automated technology. United has been flying this aircraft since 1982, and they have never had an accident or incident resulting in damage to the aircraft. This, in part, is a result of the extremely good engineering of the aircraft. There has been only one incident requiring an NTSB investigation which was later discontinued.

A specific example of one of the benefits of automation is the fact that United has never had a reported altitude bust on the Boeing 767 when the altitude was correctly set.

Operational Crutches

One of the lessons learned regarding new technology aircraft is that we should not build operational crutches to get around improper designs. An example was given to illustrate the importance of this lesson. During the early days on the 767, a problem occurred (which has now been fixed) with the electronic fuel control. An over-sensitivity in the engine EGT (exhaust gas temperature) sensors occasionally caused spikes in the EGT data which, in turn, could lead to an automatic down trim of the engine. This was a potentially serious problem, particularly during takeoff. The engine manufacturer promised to reprogram the engine control software, but the air carrier management felt that a temporary fix or 'operational crutch' was necessary until the permanent fix could be implemented. A new operational procedure was instituted which specified that the EEC (electronic engine control) should be turned off during takeoff. However, in turning it back on shortly after takeoff, a crew inadvertently manipulated the fuel control switches, which were located close to the EEC switch. This resulted in the shut down of both engines, which were soon restarted.

In this example, a human engineering design, a management decision and a fast action on the fuel control switch all came together to contribute to a serious incident.

Training/Operational Procedures

In training programs, it is important to remember that the pilot is flying an aircraft, not a computer. Due to the novelty of the technology, some early training programs emphasized the automatic and computer aspects of the aircraft with some loss of emphasis on basic airmanship. As a result, instruction in fundamental flying knowledge, such as altitude and power settings to effect different configurations, may have suffered. More recent training programs emphasize basic manual flying skills, including appropriate flap and power settings.

At one air carrier, some situations occurred during the 1970s on the 727 which emphasized the need to develop a crew procedure for every potential failure. The resulting training conditioned the pilot to expect that there is a procedure to follow for every failure. This operational philosophy worked well before the introduction of the Boeing 767 but did not work well on this aircraft. This is in part due to the fact that formulating procedural solutions for automated technologies in advance can be difficult because of the sheer complexity of predetermining all potential failures. But, fortunately, the 767 is very well engineered and no major problems resulted. One positive way to improve this situation is to teach pilots an understanding of how the systems work together and how they impact each other.

Understanding how the system works is further illustrated by a situation regarding holding patterns which occurred during the early operations of the 767. Some pilots apparently did not understand how the flight management computer (FMC) drew the holding pattern. While they were busy inserting the holding pattern data into the FMC, one crew failed to remember to slow the aircraft down to the recommended holding pattern speed. This, coupled with a strong tail wind, resulted in an overshoot of the assigned pattern.

A team approach to new aircraft training is important. One carrier's representative indicated that simulation is absolutely essential and improved facilities are needed.

When highly automated aircraft were initially introduced, one carrier had concerns about older pilots and their ability to adjust to the new technology. The older pilots, however, had little difficulty learning the new systems. The only difference was that the younger pilots learned more quickly.

Requalification training should be very thorough and this is an area where improvement may be needed. For example, "de-programming" the expectations of a pilot who is returning to a less automated aircraft may be necessary. A pilot transitioning from a highly automated aircraft to a less automatic one may unconsciously expect it to automatically level off at altitude, but some older technology is not capable of this.

An important issue is mixed fleets where pilots fly both sophisticated and non-sophisticated aircraft. The issue is not the individual aircraft, but mixing aircraft designated as a common type which have differing design philosophies into one fleet. At least one carrier split its fleet due to concern about this issue.

Mode Misapplication

It is possible with the new computer technology for the crew to assume that the aircraft is operating under one control mode when, in fact, it is not. This is particularly important when default modes are involved. One example of a mode misapplication which resulted in a high altitude stall warning occurred on the 767. The aircraft was climbing with the vertical speed mode engaged. In this mode, no automatic limits on vertical speed are designed into the system. This means that the aircraft automation will never over-ride or limit the selected vertical speed even if a stall is imminent or the speed is too high. The fact that this is the default mode makes it particularly troublesome due to the potentially serious consequences. Such default modes should be avoided in future designs.

Over Reliance on Automation/Electronic Map Failures

Although rare, electronic maps have failed and crews should not be trained to be overly dependent on them. It is, however, easy to become accustomed to these map displays because of their usefulness and quality. In training, the use of charts needs to be re-emphasized as well as the need to maintain good situational awareness.

When things do go wrong, there may be a reluctance by the crew to turn the automatics off. There is a tendency to try to use the automatics to cope with rapidly changing circumstances even if there is not enough time to enter the new data into the computer (Editor's note: the term "reprogram" is commonly used for this process, but technically reprogramming involves modification of the system software, not data entry). Data entry into the FMC (flight management computer) can also be a procedural concern. The early FMCs were slow and it was easy to get ahead of the display. Pilots should be trained to check the correctness of the numbers before the "execute" button is pressed.

ATC/Automated Aircraft Compatibility

Current designs for the automated navigation systems interface very well with the existing ATC system as long as there are no flight plan changes. However, the reality is that changes (sometimes frequent) to the flight plan and hence the FMS (flight management system) are required for weather, traffic, enroute spacing slow downs, etc. There may be a tendency to teach airline crews that the automated systems can accommodate these changes. Unfortunately, the data entry may often take more time than the ATC environment allows.

In addition, frequent ATC changes to the flight path can render the automatic system useless because the data take too long to enter, particularly below 10,000 feet. For example, vertical navigation systems work well above 10,000 feet, but sometimes are not very workable below this altitude due to speed and altitude restrictions. Since these restrictions are often deleted from the SIDs (standard instrument departures), changes are hard to keep up with. The design of the MD-11 may not have this problem since speeds can easily be changed (reprogrammed). The integration between the mode control panel and the FMC will also be a good feature of the MD-11 and 747-400.

Another example of the problems which can arise due to the mismatch between the new automated aircraft and ATC, involved a crew mis-manipulation of the mode control panel and an ATC inability to permit the aircraft to descend when requested. As a result of the inability to descend, the aircraft got further and further off of its planned descent path. In an attempt to recover the situation, the crew shut off the autopilot and recycled the computer. This fixed the pitch problem, but unfortunately the crew did not realize that, although they were tracking the localizer, the automatic capture had also been removed. This illustrates the need to improve the compatibility between ATC and the automated aircraft, as well as the need for crews to understand how the automatics work.

The controllers need to understand the capability of the newer generation of aircraft. For example, an ATC controller may give a change in course or clearance and expect to see a change in the aircraft course displayed on the radar screen. But with a modern aircraft, a course change may not be immediate, because the crew is busy entering the new course data into the flight management computer and not executing the requested course change.

As a last point, the national airspace must be viewed as a system. Many of the benefits of improvements in the cockpit cannot be realized without improvements in the ATC system as well.

Computer Sensitivity/Maintenance Issues

There have been examples where an automatic system has caused movement of a control surface. In particular, some uncommanded flap extensions at altitude have occurred which were later determined to be a maintenance problem. Although these situations have resulted in increased workload for the crew, no serious situations have occurred. Computer over-sensitivity is a factor that should be considered during certification.

An example of computer under-sensitivity occurred during a windshear condition on a commercial flight. The changes in pitch commanded by the autopilot caused the autothrottle to inappropriately change the engine thrust. The inability of these two systems to get together contributed to a 3000 foot per minute descent rate which was arrested at about 600 feet. The pilot had to take manual control of the aircraft and elected to execute a go around. No accident resulted. In summary, the inability of the autopilot to respond adequately to the rapidly changing meteorological conditions caused large pitch excursions close to the ground.

Training and expertise of maintenance personnel are also factors. Many maintenance personnel have their primary experience with older technology aircraft yet they are now responsible for maintaining the new, computerized systems.

Design

Primary flight displays should be structured to reduce clutter, as well as to be appropriate for the mode of flight. As indicated previously, electrical failures, although rare, do occur and the designs should maintain critical flight instruments under these conditions.

Consideration should be given to improving the CDUs to reduce the current keying requirements.[1] In busy terminal areas, there should be minimal interaction with the CDU systems. The CDU does, however, invite crews to "play with it."

Soft Failures

Soft failures are situations which were not anticipated by the manufacturer, so there are no pre-specified procedures, but something is clearly wrong with the cockpit display (i.e., the failure is not significant enough for the computer to indicate a failure). Such failures cause difficulties because of the nearly impossible task of predicting them. This, in turn, causes problems in preparing appropriate operational procedures.

One carrier has had at least two documented cases of computer "soft" failures. In both cases, the display showed no electronic course line. The first time this happened, crew training had been oriented toward reliance on the electronic map and there were no pre-defined operational procedures. The crew was not exactly sure how the IRU (inertial reference unit) and the FMC were linked together. They landed the aircraft safely but were not able to correctly diagnose the problem. It was written up as a triple IRS failure which had, in fact, not happened since the display still had other navigational data. Changes were then made to the educational program and as a result, the second time this happened, the crew was better prepared for the situation. The captain simply selected the VOR mode and safely continued the flight.

Basic Standards

Basic standards regarding implementation of automation across aircraft are needed, particularly for default modes. For example, the normal default mode, when the autopilot is engaged, should be speed and pitch hold. In the example

[1] Editor's note: The Boeing 747-400 and MD-11 have improved this.

cited previously, where the default mode is the vertical speed hold, the situation would not be very comfortable with one engine out.

Minimum Equipment List (MEL)

We may do ourselves a disservice by the specification of equipment on the MEL which allows a degradation of the total system. One example is the need for an operational APU (auxiliary power unit). Under certain conditions, it is not required. Yet, this is clearly not an optimum situation if an engine failure should occur during a Category II landing.

Workload

Workload on the pilot not flying, particularly in a terminal area while the aircraft is being flown manually, can be very high.

Britannia Airways Ltd. has used heart rate[2] data to augment subjective pilot ratings of workload. Captain Stu Grieve of Britannia showed data on heart rate of pilots under various conditions. Heart rate measurements were taken for crews flying the Boeing 767 and the 737 which have very different levels of automation. Both take-off and landing flight phases, as well as different operating modes, were measured. The difference between the 767 and 737 is illustrated in Figure 9 for similar ILS approaches at Luton using the flight director. The heart rate for the 767 approach is about 10 beats/minute lower than for the 737.

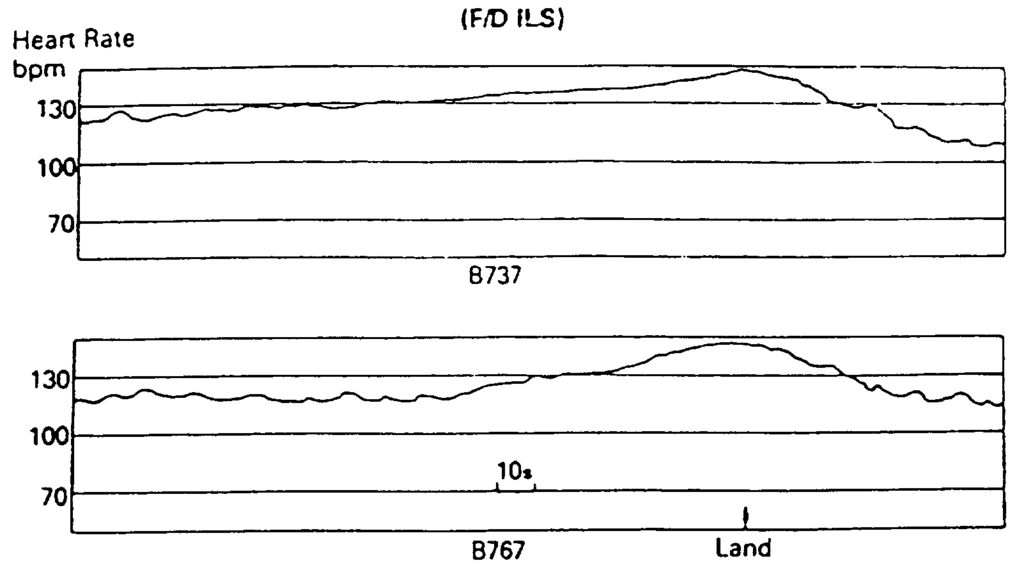
Figure 10 compares the heart rate responses during standard instrument departures out of Luton. On the 767, the autopilot is engaged at about 500 feet before the aircraft is cleaned up. On the 737, due to noise abatement procedures, the autopilot is engaged after the flaps are retracted and the aircraft is in trim.

As a last comparison, Figure 11 shows the difference in heart rates for different operating modes during a standard instrument departure from Luton in the 767. Compared to hand flying (bottom trace), heart rates are reduced when an autopilot (top trace) is used. Rates are also reduced when a flight director which is driven by the flight management system (FMS) is used (middle trace).

In summary, for the take-off and approach to landing phase, the Boeing 737 crews had generally higher heart rates than the 767 crews. However, the rates during the actual flare to touch down flight phase were approximately equal for

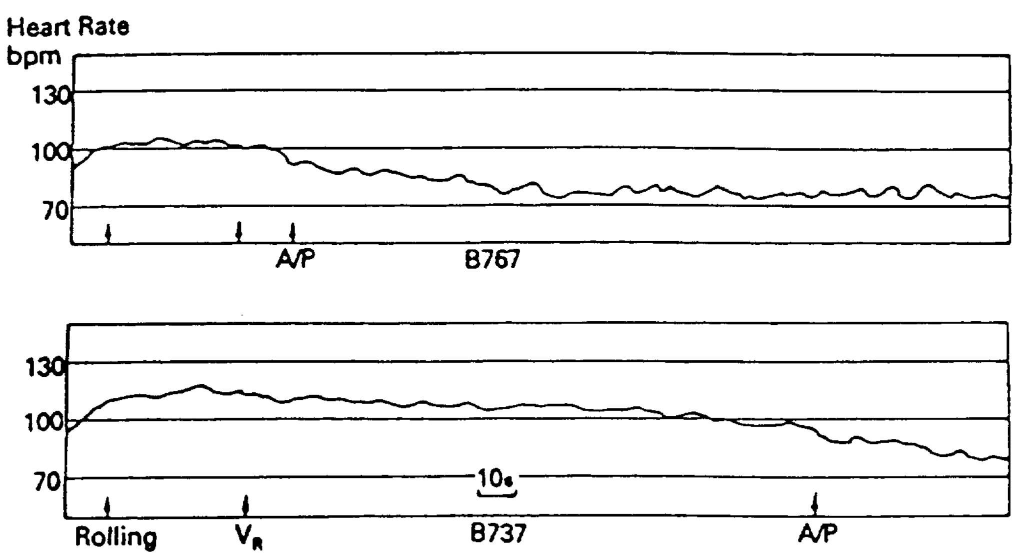
[2] Editor's note: Since heart rate can be affected by factors other than workload, data interpretation can be an issue. These data are, however, presented without interpretation.

both aircraft. These heart rates were also higher for actual flight conditions than would be expected in the simulator and this was probably due to an inability to properly simulate the real world, particularly wind conditions.



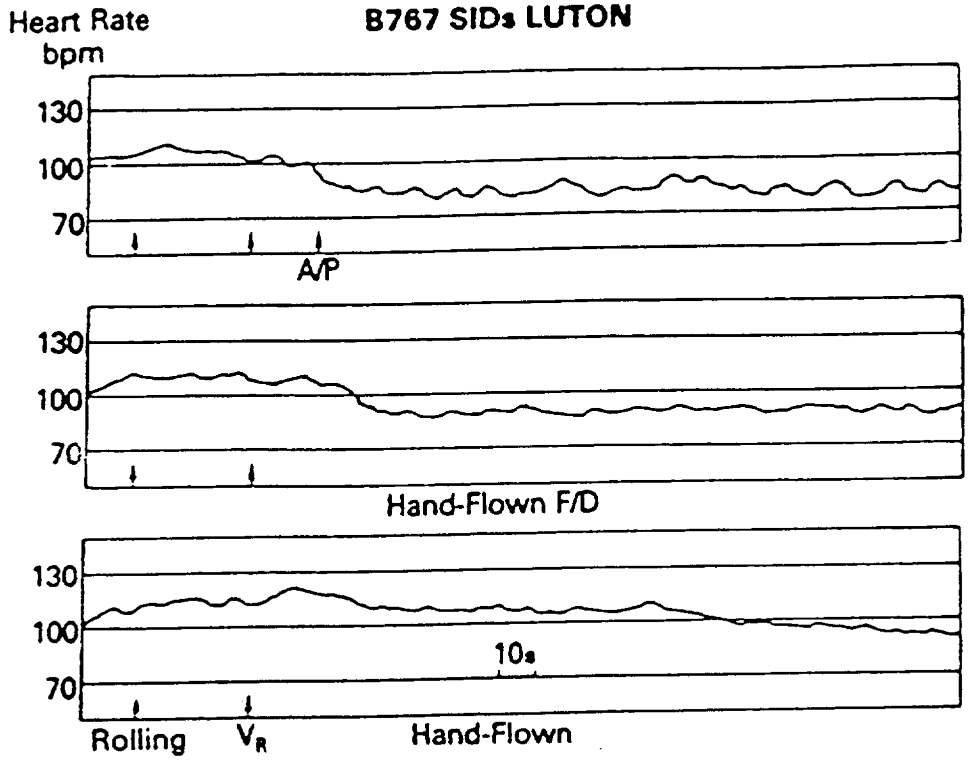
APPROACH and LANDINGS—LUTON
Comparison of Heart Rate Responses for the B737 and B767—Same Pilot

Figure 9



SIDS—LUTON
Comparison of Heart Rate Responses for B737 and B767

Figure 10



B767 SIDs—LUTON
Comparison of Heart Rates for Different Operating Modes—Same Pilot

Figure 11

CONCERNS FOR CERTIFICATION OF AUTOMATED AIRCRAFT

The Airbus 320 accident in Europe which occurred in July, 1988, just prior to the workshop, was discussed. The information available at that time was, however, necessarily incomplete. Since more complete reports are now available, the accident discussion is not included here. Several important points regarding operational certification of advanced technology aircraft were, however, raised and these are described.

> *Crew alerting*: Crew alerting should be examined carefully during the certification process for automated aircraft. In the A320 accident, apparently minimal crew alerting systems indicated the onset of an unsafe air speed. There were, apparently, no aural or tactile (stick shaker) warning devices. The only indication was the air speed indicator itself. A question, from the audience, was raised concerning aircraft designs which prevent a pilot from taking action instead of alerting him/her. Escape from windshear is another problem area.

Manual operation of an automated aircraft: Since the accident occurred during a manually controlled fly-by, the implications for operation of automated aircraft in the manual mode need to be carefully examined. Procedures for operating highly automated aircraft in the manual mode need to be fully understood.

Crew experience requirements: As a general concern, less experienced pilots may be more likely to be assigned to aircraft like the A320 because of its smaller size. The impact, if any, of relatively limited flight crew experience on safety of flight is not known.

Crew over-confidence in automation: Questions have been raised regarding the apparent over-confidence of crews regarding the capabilities of automation. In the A320 accident, the question was asked, "Would the crew have attempted such an extremely low, slow fly-by in a more conventional aircraft?" Although there is no way to answer this question, the consensus seemed to be "No." It was also stated that the A320 is a very impressive aircraft and is capable of maneuvers that are not possible in conventional airplanes.

Pilots switching between automated and less automated aircraft: The ability of crews to switch between automated and less automated aircraft in a safe manner remains a concern. If crews become accustomed to automatic protection features, will they be able to adjust to a less automated aircraft environment without considerable additional training?

Circumstances where automatic protection is a clear benefit: The A320 accident may, however, prove to demonstrate the benefit of the automatic flight envelope protection features. Although preliminary information suggests that the alpha floor protection was inhibited, the aircraft appears to have remained stable as it descended into the trees. The angle of attack protection probably had the beneficial effect of lessening the severity of the impact.

The concerns raised about automated aircraft certification are best summarized by the phrase "vulnerable systems, fallible humans." The unfortunate A320 accident was perhaps an example of one or both.

OPERATIONS SUMMARY

In his summary, Capt. Al Ogden of United stated that a combination of factors are frequently involved in incidents with automation. Some of these are:

1) *Inadequate operational knowledge*. Lack of adequate operational knowledge can lead to a failure on the part of the crew to understand how to operate the systems. Training should emphasize the integration of the systems and how they work together. We tend to teach how the system was designed by the manufacturer, not how the systems are operated or integrated. We tend to teach "How does it work?" when we should be teaching "How do you work it?"

2) *Cockpit discipline*. Allocation of responsibilities between the pilot not flying (PNF) and the pilot flying (PF) should be rigorous. For example, at United, the PF does not set the altitude window. The focus of communication in the cockpit is the mode control panel (MCP). United has been very successful with this approach for the MCP but less successful with the FMC/CDU.

3) *Cockpit resource management*: Workload needs to be carefully controlled. Too many tasks can be placed on one person, particularly when data entry ("reprogramming") is required.

4) *Split mode operation*: Operation in split mode (i.e., operation of the autopilot without the autothrottle) is discouraged at United. For example, either all autoflight or all manual is encouraged.

5) *Switch discipline*: Simply stated, this means know which switch you are going to move before you move it.

Capt. Ogden also suggested the following list of needs:

1) Better Technical Publications are needed particularly on "How do you work it?" Current training material explains very well how the systems work, but is not as good on how to work the automatics.

2) Analysis before action should be stressed and peripheral distractions should be eliminated before beginning the analysis process.

3) Tighter standardization of operational procedures is needed.

4) Better definition of tasks and priorities would be helpful.

In summary, automation is a definite plus which has many benefits including workload reduction, but it is not a panacea. Automation must work for us, and not the other way around.

PRESENTATIONS

AND

INVITED PAPERS

Invited Paper

FIELD STUDIES IN AUTOMATION

Dr. Earl Wiener, University of Miami

Susan Norman: Dr. Wiener has been conducting a field study with several major carriers regarding the introduction of automated aircraft. Although the study is not yet complete, Dr. Wiener requested and was granted permission from the cooperating carriers to present the interim findings. Part of the success of the workshop was due in part to the diversity of opinion presented. Dr. Wiener was asked, as an unbiased observer, to candidly raise some of the more critical issues regarding the pilots' operational perspective of automation. His findings and the resulting discussion are reported here.

Dr. Wiener:

This afternoon, I'd like to present an interim report on a field study I am conducting on the 757 in cooperation with two large airlines. Field studies are a window on the real world. The ASRS database is another window on the real world. By looking through these and other windows, we can learn important things about the operation of the world. The title of this study, shown in Figure 1, involves error analysis, but error analysis is just one of its features.

ERROR ANALYSIS AND PREVENTION
IN HIGHLY AUTOMATED AIRCRAFT

A FIELD STUDY OF 757 CREWS

EARL L. WIENER, PRINCIPAL INVESTIGATOR
EVERETT PALMER, CONTRACT TECHNICAL MONITOR

Figure 1

A field study brings together a large number of very diverse groups. The first job is to actually bring them together. I sincerely appreciate the whole-hearted support I've gotten from the two airlines and from the safety committees of ALPA. I particularly appreciate it because both of these airlines in the last few years have had acquisitions and other major challenges. It would have been very easy for them to keep a proposed research project on the shelf.

As a historical perspective, in 1979, I came to NASA-Ames to work with Ren Curry on a new automation project. We spent a year trying to figure out what the automation project should be. I felt it would be interesting to get out into the field where real people were doing real jobs and see what was going on. Ren launched a study on the Boeing 767 and we agreed our main interest was in crew transition. We wanted to see what happened in those early months when people transition from traditional aircraft to those with new technology.

That study was done at Republic Airlines. It was ideal for what I wanted to study. They had experienced, traditional DC-9 pilots, one of the largest DC-9 fleets and were transitioning into MD-80s. The MD-80 was the first of what I considered modern aircraft in the Republic fleet. So except for whatever military or corporate experience their pilots might have had, the DC-9 represented their most advanced technology. Furthermore, since they were transitioning from a DC-9, the 2 crew versus 3 controversy would not be a factor in their transition to this new advanced cockpit technology aircraft.

AUTOMATION FIELD STUDIES

Wiener (1985)	***MD-80***	***Crew Transition***
Curry (1985)	***B-767***	***Crew Transition***
Wiener (1988)	***B-757***	***Error Analysis*** ***Crew Coordination*** ***Training*** ***Workload***

Figure 2

My present study on the 757 seeks to extend beyond just crew transition into flight crew errors in advanced technology. I'm interested in crew coordination particularly in the modern aircraft. Training, which is an obviously important factor, has long been of interest to human factors investigators. Finally I want to talk about workload and workload management.

WHY DO FIELD STUDIES?

- ***Realism of the operational world***
- ***Line crews are untapped source of data***
- ***Problems often do not appear until years of line experience***
- ***Opportunity for an impartial "outsider" to study the system***
- ***Feedback to:*** ***operational world***
designers
research world (NASA)

Figure 3

Why are field studies important? One reason, from a researcher's point of view, is that they give us a chance to get out of the laboratory into the real world. Line crews are a great source of information because they are the ones actually involved. There is a strong feeling on the part of line crews that their experience and advice are not being sought. Too often, only the perspective of management pilots or officers in the union are solicited, but line pilots are the ones who see (and know) the way these airplanes operate in the real world.

There is a lot to be said for this view. For as you know, many problems do not appear until after the airplane has "matured." Line flying is the acid test of design. You never really know how a design will work until it gets out on the line and is flown under a variety of conditions. Finally, one focus is to provide feedback from the operational world to those who are not in the operational world.

A final important factor is that this research is impartial. I do not design, sell, or operate aircraft. My purpose here is to be able to feed back the results of my research to those who can use it—the operational world, designers of the aircraft and their systems, and the research world.

BASIC INFORMATION SOURCES IN FIELD STUDIES

- ***Questionnaires***
- ***Interviews—crews***
- ***Interviews—check airmen***
- ***Attendance at ground schools***
- ***Jumpseat observations***

Figure 4

A basic source of information in field studies is questionnaires. We have an elaborate set of questionnaires for use with volunteers. We also use face-to-face interviews, one-on-one, or one-on-two with the crews. I interview check airmen, management pilots, simulator instructors and ground crew instructors to get their views—what they like and don't like. I also attended ground schools at both airlines and have made many jumpseat observations.

Let me also mention the source of our volunteers. Once the study has received approval from management and ALPA, we appeal for volunteers with a form for them to sign up on. They fill in their own ID code and no copy of the ID codes are retained after the data have been analyzed, so we really do not know who the people are. We got 201 volunteers out of this process.

Figure 5 shows all of the seats previously held on the airline. It averages about 3 seats per person. The 727s predominate. The 727 is the only airplane common to the two participating airlines. It is the main source of pilots to the 757 largely due to seniority reasons. Although the pay scale is not much more than a 727, it's the next logical step in career progression. An interesting fact is that people do not tend to stay on the 757 very long. They leave the 757 to fly the heavier aircraft. When I went through transition ground school with 4 others, only one of them did not have a bid for a heavier airplane in a very short time. This, of course, creates cost problems in training for the airlines.

SEATS PREVIOUSLY HELD

AIRCRAFT	***CAPTAIN***	***F/O***	***S/O***	***TOTAL***
DC-9	***132***	***28***	—	***160***
727	***81***	***113***	***124***	***318***
A-300	***4***	***7***	***13***	***24***
DC-10	***7***	***42***	***35***	***84***
747	***4***	***40***	***42***	***86***
L-1011	***0***	***26***	***11***	***37***
TOTAL	***228***	***256***	***225***	***709***

Figure 5

Figure 6 shows the seat these pilots held immediately before going to 757 school. The 727 predominates. You may wonder about those people who held captain's positions in heavy aircraft. There were two reasons for their 757 bids. One significant reason was that they got tired of international and other long flights. However, the major reason was that they were interested in the new technology. And crews were bidding downward into lower paying seats because they wanted to experience the 757 technology.

The same motivation seems to be true of others. There is not much of a money advantage in moving from the 727 to the 757. The driving motivation was flying the most modern plane. It was an entirely personal motivation which very much affected the attitude these pilots had as they went through training and onto the line.

Now I'd like to show you one of 36 attitude questionnaires. These are Likert or "intensity" scales which measure attitude. The questionnaire makes a positive or negative statement. The respondent either agrees or disagrees with the statement, at some level of intensity. The scale goes from strongly agrees to strongly disagrees. Figure 7 is one example.

	SEAT HELD IMMEDIATELY PRIOR TO 757 SCHOOL			
	CAPTAIN	*F/O*	*S/O*	*TOTAL*
DC-9	*20*	*6*	—	*26*
B-727	*61*	*32*	*9*	*102*
A-300	*0*	*0*	*6*	*6*
L-1011	*0*	*2*	*3*	*5*
DC-10	*6*	*3*	*5*	*14*
B-747	*2*	*8*	*3*	*13*
TOTAL	*89*	*51*	*26*	*166*

Figure 6

Figure 7 shows an attitude question on the problem of error and automation. It is more typical of the kinds of responses in this study. The responses are almost split down the middle as to agreement.and disagreement There was very little strong agreement or disagreement on this question. You could probably not collect data with a more symmetrical curve if you tried.

We should stop talking about "pilot opinion" as if it's uniform, because the answers we received are varied. For example, one question involved altitude alerts. The MD-80 does not have an aural tone on the altitude alert and the air carrier's fleet had about 136 DC-9s with aural alerts. They also had 7 DC-9-80's (MD-80s) without them. When I asked crew what do you think about not hearing the aural warning, the answers split right down the middle. Half of the pilots said they feared they might now bust altitudes because they had been flying DC-9s for years with the aural alerts. The other half said it was good riddance. They said we've got enough tones in the cockpit already. It may not be possible to standardize based on pilot opinions.

The first series of questionnaires was in 1986 (light columns). The dark columns show results from series of questionnaires given in 1987. The questions were the same on both.

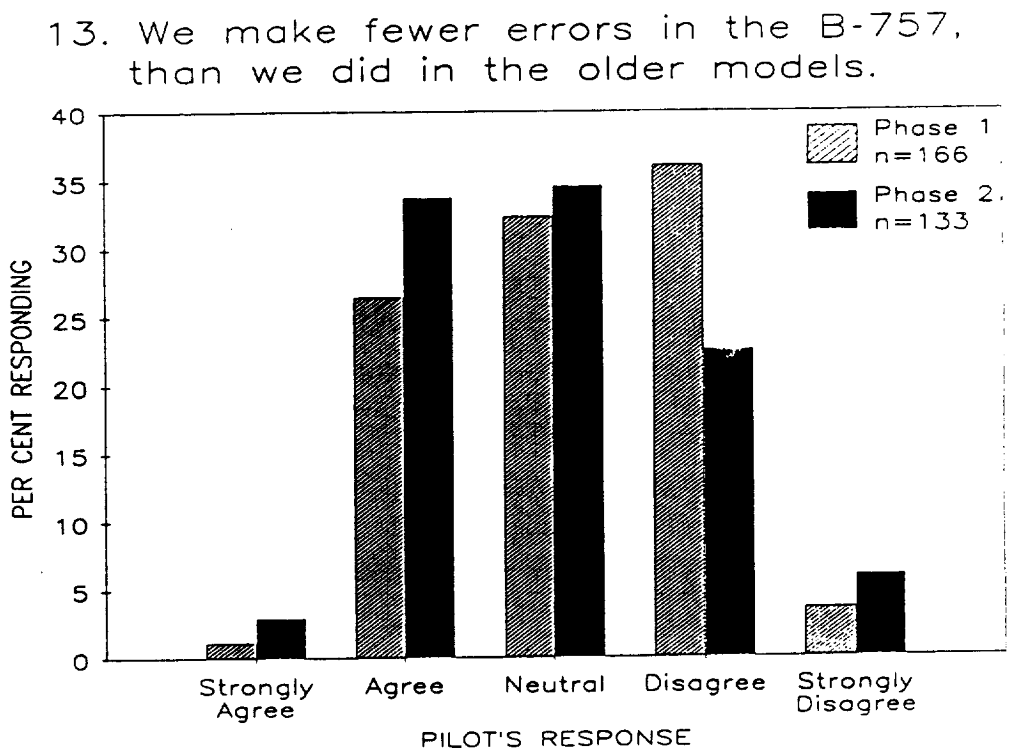


Figure 7

The advance of automation has been based largely on three assumptions which Ren Curry and I have questioned. The assumptions are:

1) Automation will reduce workload. (This was the basis of the President's Task Force endorsement of the 2-man cockpit; so that automation could take the place of the third crew member).

2) Error will be reduced. This is a traditional engineer's approach to reducing error—to automate and try to remove the human, "the source of the error," from the operating loop. I question this because even though automation does change the nature and location of human error, it does not eliminate it altogether. In fact,

we believe that automation can be an amplifier. It tends to tune out small errors and create an opportunity for gross errors.

3) Automation will be uncritically accepted by crews. We can show that automation is accepted by some and rejected by others, and that some parts are accepted while others are rejected.

We found that there was also concern about safety. Basically, pilots liked the airplane and the automation. Many did not feel it was an advance in safety because of the opportunity for error. For example, one question was to relate an error that the pilot had committed or seen someone else make. A very large percentage of the answers were altitude bust errors which occurred for a variety of reasons including human error.

An interesting thing about the 757/767 and the A310 automation, is that it creates an opportunity for new or unseen errors. For example, names of waypoints and identifiers must now be stored in the data base. Now pilots must be able to spell. If they are cleared to an intersection which is not on the LEGS page, they must be able to spell. It's not unusual to hear on the radio, " You are cleared to so and so intersection." The pilot responds, "How do you spell that?" Of course, the FAA created this problem when they went to 5-letter words for intersections. For example, if you were cleared to the Bridge intersection in San Francisco, how do you spell bridge? It's BRIJJ. But, in the Seattle area, you might be cleared to an intersection pronounced "Laker," but spelled LACRE.

Another example involves waypoints. A flight from Dallas to San Francisco, for example, passes over 2 Las Vegas's—LVS in New Mexico and LAS in Nevada. If you were cleared direct to Las Vegas and picked the wrong one, there is a very good opportunity to penetrate a MOA (Military Operations Area).

I rode in a 767 from Dallas to San Francisco. I didn't say anything about the Las Vegas problem but I had been thinking about it. During the trip the captain said let me tell you something my co-pilot did last week. "We were cleared to Farmington, which is FMN and in northern New Mexico. My copilot reached down and punched in FAM and we were ready to go to Missouri. Of course the moving map display saved us." The point is that a new source of potential error has been created. (Note: late in 1988 a pilot submitted an ASRS report. He had done just that. He punched in FAM and soon after noticed a distance to the next waypoint of 1100.)

The ALPA mapping committee is concerned with the naming issue and they gave me a list of interesting intersection names (Figure 8).

INTERSECTION NAMES IN NEW JERSEY AREA:

BIGGE,	*BOGGE,*	*BUFFY,*
HARTY,	*GOOFY,*	*KITTE,*
KIPPI,	*FLYPI,*	*CATTE*

Figure 8

The examples in Figure 8 are all within about a 4 inch square on a high-altitude chart of the New Jersey, Eastern Pennsylvania area. Try reading that list 3 times quickly without stumbling over it. This, of course, is not peculiar to automation but it is a problem with ATC with any type aircraft. I showed this slide at a meeting in Washington in December in 1981. A staff member of the Canadian Safety Board came up later and told me that they recently had a loss of separation—a very near midair collision. The intersection names were confusing (BADDE, BANNY) and contributed to the problem. Sometimes I wonder if there is any human engineering at all, considering the Korean 007 incident, and with names of the tracks in the North Pacific like NIPPI, NINNO, NOKKA, etc.

Figure 9 indicates the results of a question regarding workload. The distribution of answers is my favorite—a very nearly perfect symmetrical distribution. It shows the answers from qualified 757 pilots.

Comment from audience: Doesn't the symmetrical distribution of the answers say something about the question? How do you validate the question? Or does it also say that the question, itself, may not be important?

Response: If you mean the wording of the question, it is all-important.

As to whether the question, itself, is important, it is necessary to see all 36 questions together and then look at the ones that are grouped. This morning I've only been showing fragments of the data.

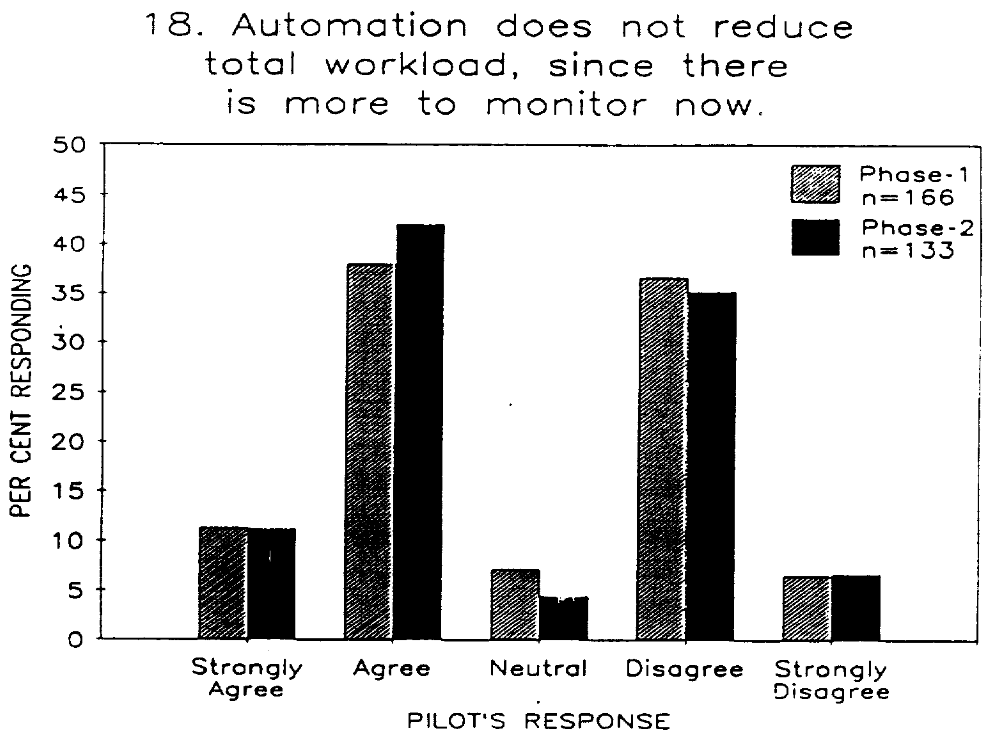


Figure 9

Comment from audience: Earl, one thing that this might lead us to look at is the amount of negative carry over from what's called Phase I ground school/Phase II simulator type training where there is a very strong emphasis on using the automated features. Early in the introduction of our airplanes in 1982 there was a reluctance to accept automation, but, as the pilots became more comfortable, they not only accepted automation but became more dependent upon it. Some training programs in the initial phase of ground school had this emphasis. This question may indicate a negative carry over as a result of the fact that the pilot has not been trained to look out the window or because he just does not have the time because of his workload. The question is, is it pilot-induced workload or is it man-made workload because of the design of the aircraft? Or is the basic problem the design of the training program?

The most consistent complaint we hear about the training program is that too much time is spent on the CDU and on the automatics, and not enough time on the basic flying of the airplane.

Response: There is considerable concern about this question of the amount of time spent focused inside the cockpit by both pilots when the aircraft is below 10,000 feet coming into a terminal area. This is something we really must explore.

There is a movement that Ren Curry first identified when he talked about "turn it off" training. As people gained experience with automation, more and more they were doing the opposite of what was expected. They started turning it off below 10,000 feet coming into the terminal areas particularly in an area like Los Angeles where "musical runways" or changes in runway are frequent. This is a training problem, a standardization problem, and a crew coordination problem as well.

Much of "who does what" breaks down in the terminal areas and if you ask line pilots or check airmen, the one thing they are concerned with is heads down in the terminal area. It is interesting that I heard the same thing 5 to 7 years ago when I did the MD-80 study. The MD-80 doesn't have half of the heads down opportunities that the Boeing 757 does. Essentially, the MD-80 has a mode control panel, but not a CDU.

That is one of the problems with the workload question. More and more people are saying essentially, "turn it off" if you get busy. You can see why I call that the *paradox of automation.* (Figure 10) When the workload gets heavy you turn off the thing that was designed to reduce the workload. Now again, is it a training problem? Is it a crew coordination problem? I think more than anything else it is a concept problem. There is something wrong with the basic concept of the design of the automatic features today. And that's why I say that years from now we'll look back and call this the era of clumsy automation.

THE PARADOX OF AUTOMATION

"A LOT OF TIMES WE JUST CLICK IT OFF AND GO BACK TO MANUAL IF THE LOAD BECOMES HEAVY."

- 757 pilot

Figure 10

Question: Is the automation the problem or the interface with the automation?

Response: I'm not making a distinction. Clumsy automation in my mind refers largely to the entire program.

Comment from audience: I am confused. Are you only addressing the reduction of workload when you mention the possibility of using automation to get rid of excessive workload? If you consider the new systems automation in the cockpit such as the FMS and the advanced autopilot, which have not been mentioned, it is another story. The present transports only address the way that the flight engineer has been removed by management of flight engineer duties. Now we are addressing a whole new set of tools.

Comment from audience: I'd like to comment in this area too. I think that the statement about automation—turning off the CDU or the autopilot and using automatic flight coupled with a CDU was ambiguous or misleading. This is quite a different issue from turning off the EICAS or the other automated systems and flying the airplane in a truly manual state.

Response: I don't think anybody has any argument about the EICAS. The problem is control in navigation or the speed control aspects. But this is essentially an interface problem. The CDUs are difficult to operate and a sizeable number of experienced crews were saying, "when the workload gets heavy I click it off."

Comment from audience: Is this almost a mis-use of the automation? For example, the crew should not try to reprogram under those conditions. The ASRS has been getting a lot of incidents where the pilots say "we shouldn't have been reprogramming." In many cases, it's not the way they were taught, but they reprogram anyhow. This concern about aircraft and their automation may have been overstated. Some of the problems we see may not be related to the automation itself, but arise because we use less than optimum procedures and then do not train very well for the less than optimum procedures. The automation is then judged as no good. That, of course, is very much overstated. In ASRS structured callbacks to pilots, we ask how they handle this very real problem. More and more pilots are responding, "I only reprogram when I can."

Response: This is a delicate balance we must reach. Another aspect is an ATC system that simply is not cordial to these aircraft. The classic case is coming into Los Angeles from the east where we are having problems, because of all the reprogramming required. The crew is set up for 24R and about the time you get to Twenty-Nine Palms or Hector, ATC switches to 25R. If the crew is a good guesser, they know where they will end up and are ready for about 4 routes—back and forth, over CIVET, coming in over Los Angeles, one more runway change. And that's when there is a division of opinion. Should you click if off, or should you program it? There are very strong opinions about that. I don't think we're going to resolve this question, i.e., the incordiality of the ATC system, before the end of the century.

Comment from audience: Your study includes a number of pilots—their preferences and opinions, but Figure 10 represents only one viewpoint which happens to be a very powerful opinion. It is probably not fair to overgeneralize, particularly when another pilot stated, "I can change it in 3 seconds." Figure 10 is a single viewpoint whereas statistics require hard numbers. A single statement may give the erroneous impression that everybody is clicking it off and this could be incredibly damning to the system.

Response: I agree; that's a valid criticism. I did not mean to say that this opinion represented the whole population. I am trying to simply put forth a few ideas from the pilots I flew with and interviewed, and I'll try to give both sides of the issue.

Comment from audience: We understand what the pilots are trying to say in Figure 10, but a statement like this requires more detailed information to understand what is behind it. Examining only one aspect of automation from one particular reply can be misleading. We have learned a lot regarding the interface of this particular system and it can be improved. We're all working on it, but the quote on "the paradox of automation" must be used in the proper context.

Response: I agree, but I want to describe the paradox of automation. Very frequently, but not all the time, pilots turn off the automation in response to heavy workload .

Comment from audience: It is very important to be specific regarding what aspect of automation. Exactly which systems are they turning off? They don't turn off all the automation. For example, the EICAS system is still used.

Response: Yes, that is a good point. Not all automation is turned off. Crews may turn off the LNAV, VNAV, and go to basic autopilot and flight director mode. They don't turn off the yaw damper, for example. But there is still a paradox which is not a lack of training, a lack of utility or even a lack of devotion to automation. Some aspects of this technology are occasionally inappropriate to use during the required maneuvers of one particular system.

Comment from audience: From the standpoint of our operations, until the advent of the 757/767 aircraft, when did anyone ever think you could make an NDB (non-directional beacon) approach on an autopilot? We suddenly had an airplane that not only gave you an autoflight system that you could do an NDB approach on the autopilot, but it gave you a moving map so that you not longer had to put your finger on the chart and follow along as you were also flying the approach.

We put all this information in front of the pilot and showed him how to use it. He was trained on this tool and given the "Madison Avenue" approach about how great automation was by the manufacturer, the vendor, the public in general. Then, when the pilot flew into the Miami area, the controller told him, "maintain 220 knots until further advised and expect clearance for an NDB approach." And shortly another ATC clearance to "Slow to 170 knots." At that point, the pilot must slow to 170 and configure the airplane. But, the autopilot won't respond fast enough. The only way the pilot can get out of this dilemma is to turn the automatics off, pull the speed brake, drop the gear, and get caught up.

It's not a failure of automation. It is because the man and the machine have not been able to interface with the ATC system. It's not a case of whether you have an EICAS or whether you have a yaw damper system. It's a case where the human, machine and the operational environment are not compatible. That's the real question. So, is that a paradox of automation? Quite certainly it is.

We train crews, give them tools, show them the disciplines and procedures, but they cannot make effective use of these techniques in the field. At the end of a 15 hour flight, would you rather do an NDB approach on the autopilot or would you rather do it by hand? But to force the choice of the hand flight mode, because the situation is not working the same as the training courses, creates the problem. Therein lies the paradox.

Chair's comment: The idea of Earl's presentation is to raise some of these issues and by the discussion, I believe we have identified an important issue. I suggest that we summarize this issue and continue with Earl's presentation.

Comment from audience: I'd like to support the previous statement. There is a paradox. The problem was correctly stated as well as the solution. It is working with ATC. An approach into Los Angeles is a prime example.

Comment from audience: One brief comment, just for balance. Earl mentioned that pilots haven't seen controllers in the jump seat lately. I'm getting exactly the same response from the controllers in the Centers. It has been years since the pilots have been in the Center; it goes both ways, which points out the need to look at the system in terms of the mis-match. Things like simply asking controllers to do more is not the answer to the problem.

We can ask both people to do more. More controller jump seating and more pilot trips to the Center.will certainly help coordination.

Comment from audience: I'd like to make an observation. Several times it has been mentioned that one of the problems is an ATC system which is not friendly to automated airplanes. This may suggest a conclusion that it is OK for the older airplanes. But the last minute runway shift is as bad for the 727 as it is for the 767, because the crew has still got to pull out the chart and do the briefing. We should not conclude that ATC should be more sensitive to the automated airplane or that such aircraft should be given special treatment.

Response: This is not a single problem. The fundamental problem is the ability to deal with everything from Lear jets to 767s, right on through the system and I don't see a change coming in the near future.

There is another problem area regarding what people have to do to "cheat" on the automated system. My students know how to "cheat" the computer, but I didn't think I was going to see it in the 757s. Things like getting down early so you can make it work. For example, crews do ingenious things like programming fictitious tailwinds, or inserting an altitude for thermal anti-ice (TAI) (but not turning it on) so it will get the aircraft down earlier.

I would like to discuss training next. This is an area that requires a lot more thought. There is a change in training for automation that may be qualitatively different. Questions such as, "would you introduce the automation first as most of the airlines do now?." This is a basic question, but we really don't know the answer at this time.

Skill deterioration or more dramatically, automation apathy, is another issue. In the field studies we have done, I don't see any such signs. Pilots are not concerned about it as long as they personally keep up their skills by hand-flying. In the MD-80, the pilots expressed concern, but when they went back for their first Proficiency Check (PC) (in a DC-9-30 simulator), they had not suffered any skill loss. In fact, they said they flew better when they went back to the -30 simulator and did their first PC than before they had -80 time.

Question: Were they flying both airplanes?

Response: Yes, they were at that time. Later, about half way through the study, they flew in separate schedules, based on flying only the -80 for 9 months. Each of the pilots works out his own "training program" using hand-flying, flight-director only, or occasionally raw data only. I called it the "Personal FAR" in the -80 study. About 90 percent of the people do this. Another related issue is a copilot who flies automated aircraft and then suddenly qualifies as captain on the DC-9-10 or 737-100. Skill loss has not been the problem, but our methodology may not be very sensitive to it. It's always a pleasure to find something that is not a problem.

Question from audience: Have you looked at carriers that prepare their pilots to fly automated all the time?

Response: The carriers differ on this. As a matter of company policy, one airline requires that crews do not use it all the time. Another company, for example in the -80, had a "we bought it, you use it" policy. However, the pilots would simply click it off and fly manually, when necessary.

With respect to training, the opinion of one flight manager was that there was a too rapid introduction of the technology into the training program, and not enough information on the basic airplane.

Another interesting comment from a captain about PCs in checkrides. He said, "Formerly, when I went for a checkride, the FAA was always turning things off. Now they tell me I have to turn things on. They don't want to see you operating an airplane without automation."

This comment in Figure 11 came from a young first officer and in my opinion, it generally reflects pilot attitude. They all thought that they were "going back"—going back to a 727, "going back" to a DC-10. It was a phrase we heard often.

"I'LL TELL YOU WHAT IT'S LIKE TO GO FROM THE 757 TO THE 747: IT'S THE GREAT LEAP BACKWARD"

Figure 11

As a final note, Figure 12 summarizes the high enthusiasm for the 757, although I have mentioned some reservations about the safety aspect. Workload may be increased or decreased. Of course, it appears to be increased at the phase of flight where you would not want an increase, and a decrease at the phase of flight where you would not want a decrease. I don't think that is a reflection on automation, rather that it is in the nature of the flight itself. It's a major challenge for those designing the future systems.

Some first officers are very fast. They can have route 1 and route 2 both loaded before I can even see what they are doing.

There is a great variety in time required. There can be differences between captains and first officers and the speed of each group. One person can be a whiz on computers and really loves it while another person may have a different kind of wisdom. You can see it in the training. And, of course, I only observed a small number. I talked to the simulator instructors and training captains and they confirmed this. As you watch people in the initial phases of ground school, the first officer learns quickly, but some of the captains had difficulty. But in the two weeks after they left ground school and went to the simulators, the captains had accelerated—taking advantage of their experience. In the simulators, the captain suddenly caught up.

Question: Do you think the term programming, or reprogramming, is the correct word to use in the cockpit? I think we should not use those two words.

Response: Why is that? Because you don't consider it "programming," but rather "loading data" or something like that?

Comment: It's an airplane, not a computer. I think those two words are dangerous, if one gets used to them, because we lose track of the fact that we are still flying an airplane.

Comment: In our early training, the primary reluctance for the captains was over this issue. The word "program" placed a cloud of uncertainty, especially over the older crew members. In 1982, I went through training with a group of people whose average age was 48-53. They were very, very reluctant. Some of these people had not been through ground school in 16 or 18 years. They approached the training in a very timid manner, and when the word "programming" was used, they either literally had to be held back from pressing the execute button too soon or would have paralysis when it came to placing their finger on a key and making a keystroke on the CDU. They could not bring themselves to do that because of, again, the specter of "programming."

Comment: If there could be a better word or term applied to it, I believe we could reduce probably 40 percent of our problems. I tell our people, "slow down 10 percent and improve your accuracy 40 percent," and you could probably take away another large percentage when you simply change the terminology.

Response: There are still difficult problems to solve on the CDU, like entering a route with two jet airways intersecting each other. And, you may not want to call it programming, but that's what it is. It is not simply data entry. For example, there

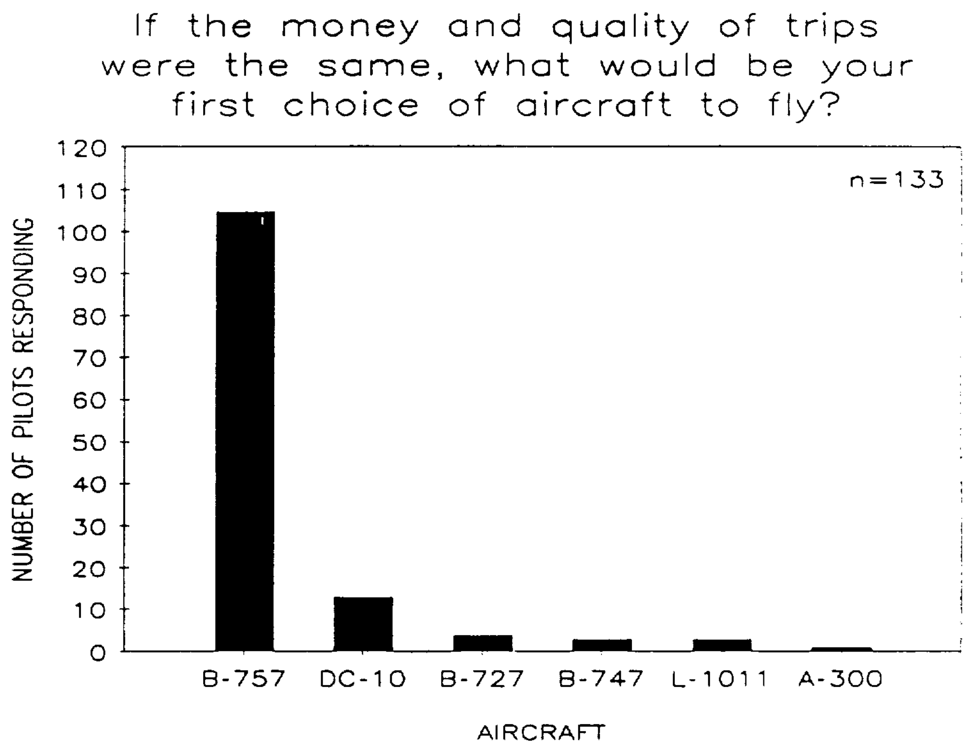


Figure 12

I have data that I don't have time to present to you today, but it will be published in the final report for the research project. The final questionnaire will have information on how many ADF approaches, VOR, localizer, CAT-II, CAT-III, autoland and "man-made" approaches.

Question: On the programming of the CDU, from your observation, what is the distribution on the time required to reprogram the CDU? For example, in a musical runway situation requiring reprogramming.

Comment: You know, of course, that this is not the only time that reprogramming is required. Reprogramming time is largely a function of experience. There seems to be a critical point at about an experience level of 200 hours. It was about 50 hours in the MD-80, and the differences were not as great as with the 757. But in the 757 it took about 200 hours to get really proficient. Some of the pilots are very proficient.

are two jet airways and you have to fly one, and then change to the other, and there is no named intersection. In my mind, that's programming.

Susan Norman: In the new technology, we should be clear about the meaning of terms. We have prepared a list of terms (see appendix) and hope that they will be useful. I hope you will consider Earl a valuable resource for discussion, but in the interest of time, I must conclude this discussion.

THE ADVANCED AUTOMATION SYSTEM (AAS) FOR AIR TRAFFIC CONTROL

Alden Lerner, Federal Aviation Administration
Washington, DC

PURPOSE

The advanced automation is tomorrow's air traffic control system. It will provide a new automation system that includes new computer hardware, software and improved controller work stations. The advanced automation system will provide:

- the capacity to handle the projected traffic load through the 1990s and beyond,
- the capability to perform new functions to be introduced into the ATC system through the 1990s,
- increased productivity through the introduction of new sector suites,
- a high degree of reliability and availability, and
- the capability for enhancement to perform other functions subsequently introduced into the system.

APPROACH

The advanced automation system (AAS) will be designed through a top down, evolutionary, total system approach. Controller sector suites will consist of common consoles used for both enroute and terminal (approach control) functions. They will incorporate an improved man-machine interface, including the use of color displays and electronic presentation of flight data to enhance controller productivity. The advanced automation system will make possible the full integration of enroute and terminal operations in the area control facilities.

Transition to the AAS will consist of five phases:

1) implementation of the Peripheral Adapter Module Replacement Item (PAMRI),

2) implementation of the initial sector suite system (ISSS) to provide new controller work stations,

3) implementation of terminal advanced automation (TAA) functions using AAS hardware and software,

4) implementation of tower control computer complexes (TCCC), and

5) implementation of Area Control Computer Complex (ACCC) for the remaining AAS enroute functions.

Phase one, implementation of the Peripheral Adapter Module Replacement Item (PAMRI), which includes replacement of the PAM and Data Receiver Group (DRG) equipment, will be implemented prior to ISSS equipment delivery. This will provide an enhanced ability to interface with additional radars, and will provide a capability for use of higher data transmission rates for radar site interfaces.

In the second phase, initial sector suites will be installed in enroute facilities served by the host computers. The sector suites (work stations) will be the first AAS components to be operational, providing early gains in controller productivity. The consoles will feature large, multiple color displays that will provide situation traffic, weather, and flight data as well as a "look ahead" planning capability. Although each console will have its own embedded microprocessors to drive the displays and perform related tasks, most of the data processing required for controlling traffic will be performed by the host computers. First delivery of an ISSS will be to the FAA Technical Center in Atlantic City in September, 1990, where it will undergo extensive test and evaluation. First site delivery to the Seattle Center is scheduled for April, 1992. The equipment is expected to be operational at all sites by June, 1995.

The third phase will be the implementation of the TAA for TRACON functions. Following the transition to ISSS for enroute control, the old control rooms will be refurbished to accommodate the additional sector suites necessary to provide approach and departure services at the approximately 200 airports that now have their own terminal radar control rooms. Deliveries of new AAS hardware processors, software, and additional sector suites to support terminal operations will begin in 1994.

The fourth phase will be the installation of TCCCs in selected airport traffic control towers. The TCCC will include new controller position consoles with supporting computer hardware and software and new electronic displays for flight data and radar information. Controllers will use the radar data as an aid in tracking aircraft in the terminal area, as they may be required to provide limited approach and departure services. The contractor will begin delivering TCCCs to upgrade the first 150 airport towers included in the basic contract in 1994. The last site (258th, if all contract options are exercised) would become operational in 1999.

The fifth phase in the evolution to a full AAS will begin in 1994 with the installation of the remaining computer software required for the enroute air traffic control functions (ACF). Additional sector suites will be installed to enable conversion of today's ARTCCs into tomorrow's ACFs. The hardware/software associated with this step will be named the area control computer complex (ACCC). Once this is completed, the host computers at each location can be removed along with the current back-up system in the enroute centers. The completion date for this phase is August, 1998.

Included in this phase would be the addition of the Automated Enroute Air Traffic Control (AERA) software into the system to aid controllers in effective route planning. Known as AERA-1, it will probe requested flight routes to detect potential conflicts with other aircraft, violations of protected airspace, and conformity with air traffic flow restrictions. With this information, the controllers can select the safest and most fuel-efficient route available.

Future AAS enhancements not covered by the contract will include AERA-2 and, possibly AERA-3. AERA-2 would present controllers with solutions to the conflicts detected by AERA-1 and, then, pass along their decisions to pilots by digital data link. AERA-3, which is still in the concept stage, would include some degree of autonomy for the AAS computers to detect and resolve problems, make decisions and provide clearances to pilots under human direction, but without human intervention.

PRODUCTS

The scope of the AAS project includes:

- Advanced automation system design
- Advanced automation system software for both terminal and enroute ATC operations
- Advanced automation system computer hardware
- ISSS (20 Continental U.S. ARTCC)

- ACCC (ACFs—including Anchorage, Honolulu, and the New York TRACON)

- Support systems at the FAA Technical Center and the FAA Aeronautical Center.

IMPACT

The introduction of the new controller work stations and new communications networks will greatly impact the controller's physical environment. Further, the organization of the new equipment into ACFs which will result in the co-location of terminal and enroute functions in the ARTCC will impact the procedures for managing the duties of air traffic control, maintaining the systems, and organizing the work force.

The Advanced Automation System is tomorrow's air traffic control system. Its sophisticated equipment and programs will improve upon present air traffic control by:

- enhancing flight safety with new automatic separation-assurance techniques,

- increasing flight efficiency through more direct, conflict-free routing,

- reducing congestion and delays through better traffic-metering techniques,

- increasing controller productivity through new controller work station,

- handling projected air traffic growth without corresponding increases in personnel,

- providing a system life of 20-30 years; new hardware/software can be added to the basic design,

- tying together all of the FAA's primary enroute and terminal air traffic control facilities into an integrated, automated system,

- permitting the consolidation of all radar services into approximately 23 strategically located Area Control Facilities (ACF),

- providing greater system reliability through a requirement that the AAS be available 99.9995 percent of the time (maximum down time of about 2 1/2 minutes per year).

AAS DELIVERY SCHEDULE

Initial Sector Suite System
Delivery to FAA Technical Center - September, 1990
Delivery to first ARTCC - April, 1992
First site operational - October, 1993
Last site operational - June 1995

Tower Control Computer Complex
Delivery to FAA Technical Center - April, 1992
Delivery to first airport tower - March, 1994
First site operational - February, 1995
Last site (150th) operational - March, 1999

Terminal Advanced Automation System
Delivery to FAA Technical Center - December, 1992
Delivery to first ARTCC - march, 1994
First site operational - February, 1995
Last site operational - February, 1998

Area Control Computer Complex
Delivery to FAA Technical Center - January, 1993
Delivery to first ARTCC - September, 1994
First site operational - March, 1996
Last site operational - February, 1998

Invited Paper

THE EFFECTS OF AUTOMATION ON THE HUMAN'S ROLE: EXPERIENCE FROM NON-AVIATION INDUSTRIES

Dr. David Woods, Ohio State University

Susan Norman: Automation technology has been employed by other industries for many years. Although the operating environments are not exactly like aviation, the experiences regarding the technology itself are surprisingly similar. Dr. Woods was asked to select a few representative examples with relevance to aeronautics and to draw some general conclusions about their applicability in the transport aviation environment.

Dr. Woods:

I have been asked to comment on the effects of introducing new automated technology. Rather than start with broad generalizations, I have selected a variety of specific, actual cases where field studies or controlled studies have been conducted to determine the effects of new technology on both productivity and the quality of human performance. The cases that I have chosen to discuss are relevant in some fashion to aviation, and they are listed in Figure 1.

An important point is that these examples are based on field study results, not opinions. Of course, there can also be questions of interpretations in field studies. I was personally involved in some fashion in several of these studies. Some are based on reviews of other people's studies on the effects of automation. It will only be possible to discuss each case briefly but more detailed reports are included in the references.

The term "automation" has been used so much that it has taken on several meanings. In several of the examples which follow (process control and computerized numerical control or CNC), automation refers to autonomous machine systems because the jobs are performed in a semi-autonomous way, without direct manual intervention. The other examples concern "automation" in the sense of new information systems capabilities such as diagnostic systems.

Studies or Field Experience on the Human Role in Highly Automated Systems

- ***Computerized Numerical Control in manufacturing***
- ***Banking information systems and processes***
- ***Steel processes***
- ***Nuclear Industry:***
    - ***Computerized alarms systems***
    - ***Disturbance Analysis systems***
    - ***Computerized procedures***
    - ***Expert systems***

Figure 1

TECHNOLOGY CENTERED AUTOMATION

These cases all illustrate a common underlying philosophy of automation which has been called "technology centered" automation. The assumptions of this approach to developing new levels of automation are noted in Figure 2.

The issue is not to automate or not to automate; it is how to automate. How should the level of technology be increased? What should we do with the technological capabilities? Choices can be made about how to introduce the technology which require careful thought. There is no technological imperative—only one way to use technology.

The fundamental assumption behind most automation development is that people and machines are comparable; one can be substituted for the other on each subtask; and the tasks to be performed are independent. In other words, changing the allocation on one task has no effect on other tasks. It has been difficult to make progress in the field of human factors because we have been locked into this "can we substitute a machine for a person" approach to function allocation.

Technology Centered Automation

philosophy of person-machine comparability

allocate to people tasks that are expensive or difficult to assign to machine

system problems are solved by attempting to shift human functions to the machine

person is often a convenient and cheap manipulator or perceiver

de facto human role: "plug the holes in the thoroughness of the designer's work"

Figure 2

The result has been that tasks which are expensive or difficult to assign to the machine are allocated to the people. We tend to automate the tasks that are automatable at a reasonable cost. If there are system problems, they are usually dealt with by transferring more human functions to the machine—solve performance problems by reducing the human's role in the system. There has been no global systems context where the person and machine work together.

There is also a tendency to use the person as a convenient and cheap manipulator or perceiver for the machine, because it is difficult to automate perception. This is particularly true in the development of expert systems as we shall see later.

In the technology centered approach to automation no thought is given to the human's role in proper system function. Instead, as Jens Rasmussen has pointed out, the *de facto* human role is to "plug the holes in the thoroughness of the designer's work" (Rasmussen, 1979).

COMPUTERIZED NUMERICAL CONTROL

One of the early automation cases, which is often misdescribed in terms of what actually happened, involved computerized numerical control (CNC). This case, summarized in Figure 3, has been one of the most investigated cases of changes in automation. The original goal was simply to eliminate the skilled machinist to save money. What actually happened depends on the exact machine application, but in general, the human role, as well as the skills needed to carry it out, changed (cf., Noble, 1984; Corbett, 1985; Kidd, 1988). The operator was now responsible for preventing gross machining errors such as machining the wrong part. But if the operator was not skilled and knowledgeable in the tooling process, unscheduled down time and gross machining errors occurred.

Computerized Numerical Control

original goals: ***eliminate skilled machinist***

actual results: ***changed human role and skills to avoid unscheduled downtime and to minimize the costs of machining errors***

critical human role is to adapt to unanticipated variability with success depending on:

- ***machinist learning and inferring what is the computer plan,***
- ***where it is vulnerable to breakdown in the face of different circumstances (e.g., tool wear),***
- ***how the computer plan is progressing in a particular case,***
- ***devising and using ways to directly or indirectly control the CNC system***

Figure 3

The critical human role was to adapt to "unanticipated variability." Conditions still arose in the machining tool process that went beyond the capabilities of the CNC machine programs. The human had to help the machine to adapt. The machinist now had to understand something about the plan resident in the computer program. He did not have to be able to duplicate it or to write the program, but he did have to understand what it was trying to do—its intentions. He had to understand where it was vulnerable to breakdown and what factors gave it trouble.

Tool wear, a classic case particularly in the earlier systems, was a factor that could challenge the automated systems. The operator monitoring requirements went up—as the machining progressed through a run, the operator needed to understand how the plan execution was progressing. Was it going off track? Was it starting to have problems? This required supervisory control (a theme which repeats in many of the cases to follow). As a supervisor, the operator now had to adjust and redirect the system occasionally. The designers, however, rarely provided convenient ways to accomplish this because they did not think about the machinist's role. It was up to the machinist to devise new ways to control the CNC systems.

BANKING INFORMATION SYSTEMS

Another example is a study of a shift in the information technology used in the banking industry (Adler, 1986; summarized in Figure 4). Again the exclusive goal was to reduce the number and skill levels of the people in the system. The term "peripheralization" of the human role was first applied by Adler during this study. What he meant is that, as the level of automation increases, the person's role is to manage and care for the health of the automated system. The new human role was to manage the operational environment so that the system would stay within its range of capabilities.

While there were many detailed variations in the skill consequences of this particular example, there was an overall increase in skill requirements, because the main role of the people in the system had changed. They were primarily dealing with anomalies around preplanned routines. There were many preprogrammed specific banking transactions, but customers often had situations that were a little different. Somehow the bank operators had to understand what each special case meant in terms of the automated system. They needed to understand the banking processes as well as the automation. They could no longer have a narrow task orientation as they had in the pre-automation days. A broader perspective of the whole system was now required.

There was also a great deal of concern because the automated system was much more fragile. The degree of inter-coupling or interaction between the system parts, as well as the level of integration among the various aspects, was increased with more automation.

Banking Information Systems:

original goal: ***reduce number and skill levels of tellers***

actual results:

1) ***peripheralization of human role***
2) ***increase in teller skill requirements: main role is to deal with anomalies and contingencies around preplanned transactions***
3) ***fragility of new system due to increase in level of inter-coupling***
4) ***data integrity is a major issue in part due to low detectability***
5) ***new error vulnerabilities/consequences (error frequency/cost relationship changes)***
6) ***need for greater training in several areas including the overall computer processing system and accounting procedures to avoid or correct errors***
7) ***in general, the increase in level of automation produced:***
   - ***new types of task responsibility,***
   - ***new degrees of abstractness of tasks,***
   - ***new levels of task interdependence.***

Figure 4

Data integrity also became a major issue. A tremendous amount of effort was spent to be sure that the data in the system were accurate. If they became corrupted, wide-ranging effects on the system were possible. This was important, in part, because of low error detectability. The result was an increase in the need for "situational awareness," i. e., an understanding of the state of the overall system and what it is doing because errors must be detected. These errors, in this case, are not necessarily human errors, but simply bad data in the system.

Another common theme is that changes in level of automation produce a shift in the kind and cost of errors. It was not simply minimizing errors. For the first time, new kinds of errors were possible while others were made impossible. The vulnerabilities and consequences of errors had changed. The frequency of some kinds of errors may have been reduced, but some of the new failure forms had different, higher consequences. The concern was the fragility of the system. It was now difficult to localize and contain errors, since they tended to spread throughout the system in ways that were hard to detect. Usually mistakes were apparent only when something came crashing down, such as a customer related problem.

As a last point, the need for greater training was not anticipated and there was quite a bit of scrambling. Again, remember that the initial reason for instituting automation was to save money by decreasing the skill requirements. But what actually happened was people had to understand more about the overall process—accounting and the banking processes. They had to have some understanding of the overall computer processing system. Otherwise, they could not do their job of helping to avoid or correct errors in the system.

In summary, this example illustrates how shifts in level of automation can produce new kinds of task responsibilities and new levels of abstractness which in turn require more conceptual skills on the part of the system operators.

PROCESS CONTROL INDUSTRY

A classic example of automation in the process control industry occurred in a steel plant (Hoogovens Report, 1976; summarized in Figure 5). Again, the original goal was to reduce the number and skill level of the operators. The actual results were quite different. For a period of time, down time was actually increased due to automatic system breakdowns. An in-depth study of the effects of automation in this case was prepared and the report states, "the need for the operator to intervene directly in the process is much reduced, but the requirements to evaluate information and to supervise complex systems is higher."

Steel Processes

original goal: ***reduce number and skill of operators***

actual results: ***increased downtime due to system breakdowns***

"The need for the operator to intervene directly in the process is much reduced, but the requirements to evaluate information and supervise complex systems is higher"

automatic control or manual control; no provisions for supervisory control

- ***no mechanisms for operators to understand or track what the automatics were doing***
- ***no mechanisms for operator to direct the new automation***
- ***authority/responsibility double bind.***

Figure 5

Again the theme is the same as in the banking case. The problem was the designers had designed the plant to work in one of two modes: either automatic control or manual control. Obviously, there was a manual backup to run the system, but there were no provisions at all for supervisory control and no mechanisms for the operator to understand or track what the automatics were doing. In fact, initially, the operator received barely any training or information about what the automatics were about at all. In short, there were no mechanisms for the operators to direct the new automation.

The situation was made even worse by an authority/responsibility double-bind. The operator was (or thought he was) responsible for the proper operation of the system. The effective authority was, however, in the hands of the machine automatics. The operator was there just in case anything happened or to help the automatics in situations that were not practical to automate at this time. In actuality, the operator was unable to coordinate control of the system. The resulting level of performance was the performance of the automatics alone. Unanticipated situations arose which went beyond the capabilities of the automatics. Furthermore, when trouble arose, the consequences tended to be broader because the system was more integrated following the increase in automation. The overall result was an increase in down time after the introduction of the automation.

AUTOMATED FACTORIES

A case, closely related to the Hoogovens experience that is going on today, is in process manufacturing, where the objective is the automated, or "lights out," factory (if there are no people, then there is no need for lights). Steve Miller at Carnegie-Mellon has an interesting program of research in progress in this area (cf., Miller & Bereiter, 1986; Bereiter & Miller, 1986; Bereiter and Miller, 1988). He is working with a major corporation and some of their automated lines to study the effect on the human's role. Again, the inter-coupling or relationship between the system components is increased through new automation, and the critical human role becomes fault management such as avoiding unscheduled down time. However, there has been very little support provided for this human role, as summarized in Figure 6.

Automated Factories

original goal: ***lights out factory***

actual results: ***automation increased level of intercoupling***

critical human role is fault management to avoid unscheduled downtime

---

Figure 6

NUCLEAR INDUSTRY: COMPUTERIZED ALARMS

In the nuclear industry, there are a variety of cases, and I have selected a few which are representative of the important issues. These examples can be hard to dig out because, in this world as in many others, no one wants to discuss technology failures. The feeling is it would be better if, like old generals, they just faded away. No one wants to investigate what happened or why, but the lessons for the future are important

In the British nuclear power industry in the seventies, the tile annunciator alarm systems were computerized (Pope, 1978). A tile annunciator alarm is an an engraved tile that is back-lit, and each tile represents a setpoint or component status. If the variable crosses the setpoint (or if a component is in a particular state—pump off), the tile lights up. If there is another setpoint on the same variable, it is represented by a separate engraved tile. There can be thousands of these tiles in a nuclear power plant, and an avalanche of alarm signals occur during plant upsets.

There are serious difficulties associated with fault management in this situation related to data overload (Lees, 1983). A computer solution was devised to deal with the shortcomings in the old system. The computer based alarm system contained the same raw alarm data—setpoint crossings and component status changes. This data was now organized in a chronological list (in part, because it was easy to build with the technology of the day).

When the new computerized system was installed, it was discovered quickly that the operators could not effectively monitor and track plant state during upset conditions. The old pilot annunciator system had to be re-introduced. The reason for this failure was that the designers of the new system did not understand some of the serendipitous benefits of the old tile annunciator system (the inherent spatial organization) which were eliminated by the shift to the new technology. In the old tile annunciator system, even though there were huge numbers of signals, they were spatially distributed. Each tile was spatially assigned to a location and the operators could determine some things about the overall problem based on the pattern of lighted tiles.

The old system made use of human pattern recognition capabilities, and, with experience, operators could learn to recognize patterns (Kragt & Bonten, 1983). A chronological list of very raw alarm information, however, comes in fast and gets very long, very quickly. The operator had to refer back down the list and to scroll back and forth through the screens trying to find out what happened and to build an integrated picture out of the raw alarm data. This was extremely difficult to do with the chronological organization, exacerbating and not relieving the data overload problem.

This theme, summarized in Figure 7, is common in many of the information system oriented increases in automation. Designers will be technology driven and build the automation that makes the most sense in terms of cost and the use of the technology. But the cognitive consequences for the problem solving task, fault management in this case, are rarely considered.

Nuclear Industry: Computerized Alarms

shifted from tile annunciator alarm systems to a form of computer based alarm system

original goal: ***improve alarm systems, use computers***

actual results: ***the tile annunciator system had to be reintroduced***

serendipitous benefits of the tile system were eliminated in the computerized system that greatly increased the difficulty of fault management

Figure 7

Another example occurred on ships when a new electronic display and control system was introduced into the engine room. Automation designers frequently try to finesse the cognitive consequences of changes in the person-machine system by relying on the flexibility of computer based systems–the designer's only responsibility is to make all of the data available and accessible; it is the domain practitioner's job to find the right data at the right time. However, a case described by Moray (1986) illustrates how flexibility alone is not enough in the development of more automated information systems.

In this case, a new, fully computerized ship engine control room was developed. There were three CRT screens, and the operator could call up a variety of computer based displays and controls on whichever CRT he or she desired. A human factors review of the system predicted that, at some time in the life of this system, the operator would call up the computer display for the starboard engine controls on the port CRT and the computer display for the port engine controls on the starboard CRT–a violation of stimulus-response compatibility guidelines. This could lead to an execution slip where the operator would unintentionally manipulate the wrong ship engine.

Shortly thereafter, during simulated shiphandling with the new system, this situation arose and the predicted result followed. Alarms indicating starboard engine trouble occurred. The operator correctly diagnosed the situation and attempted to control the starboard engine. He manipulated the engine controls on the starboard CRT display which display the port engine controls. If this had occurred at sea during a difficult navigation period, the ship could well have run aground.

NUCLEAR INDUSTRY: DISTURBANCE ANALYSIS SYSTEMS

The next example, Figure 8, is one of the best illustrations of a failed attempt at automation which faded away without comment or investigation. It was several projects that went on about the same time in three different countries to build "disturbance analysis" systems in the nuclear industry. The projects were attempts to address problems in operator diagnosis of faults and the deficiencies in alarm systems by automating fault diagnosis (artificial intelligence techniques were not used).

Nuclear Industry:
Disturbance Analysis Systems

multi-year, multi-million dollar projects in U.S., Germany, Japan, circa 1980-1984

original goal: ***carry out automatic fault diagnosis; reduce operator role in diagnosis***

actual results:

1) ***unable to automate fault diagnosis and did not make the operator a better diagnostician***

2) ***exacerbated operator data overload***

3) ***projects transformed or abandoned***

Figure 8

However, diagnosis in a large complex system like a nuclear power plant is inherently a very difficult task (Woods, 1988). For example, there are typically multiple faults and interacting factors that explain the pattern of symptoms. The disturbance analysis projects were unable to do automatic fault diagnosis and they did not make the operator a better diagnostician.

In part, this occurred because the data overload on the operators was exacerbated. The disturbance analysis system generated large amounts of potentially useful, more integrated information. But now the operator had the task of interpreting all this data, finding out what was useful and integrating it with the large amounts of time varying data available from other information sources. While this experience has generated more interest in human-computer techniques for managing large amounts of dynamic data, the lessons are largely going unnoticed. Today, another attempt is underway to automate diagnosis via artificial intelligence techniques. Interestingly, the label "disturbance analysis" is taboo in the nuclear industry.

COMPUTERIZED PROCEDURES

Another case (Figure 9) concerns computerizing procedural information. There were a variety of goals such as improving data retrieval from large libraries of procedural information. In the end, however, the attempt was abandoned because people got lost in the system.

The data base application in question was a computerization of paper-based instructions for nuclear power plant emergencies. The system was based on a network data base "shell" with a built-in interface for navigating the network. The shell already took into account the basics of human-computer interaction so it was assumed that all that was needed was to enter the domain information. However, several factors combined to produce a keyhole effect. These factors were the organization of the network, the standard navigation features, and the fact that power plant incidents are dynamic and new events can occur which change how the operator should respond.

In summary, the operator could only see one procedure step at a time; it was difficult to refer back to a previous step or to look ahead to see what steps have to be done next (Elm & Woods, 1985). There was no attempt to provide the operator with a broad picture of the response plan being executed or where it was going. Trials with the system revealed that the people who used the database shell to generate the system got lost. The people who wrote the procedures and tried to use this system got lost. Experienced operators, who knew what step in the procedures should be executed given the current plant state, also got lost.

Computerized Procedures

Shift from paper based to computerized procedures.

original goals: ***improve maintenance of procedure information, improve operator procedure retrieval, ensure rote procedure following, use new technology***

actual results: ***attempt abandoned due to user getting lost in the network of data***

Figure 9

The end result was that the attempt to computerize the procedures in this way was abandoned. A side note is that a redesign was done based on a proper cognitive task analysis of procedure usage. The new design utilized several techniques to avoid keyhole effects and to support the user. Interestingly, almost all of this design could have been implemented within the base capabilities of the interface shell.

EXPERT SYSTEMS

The next case addresses expert systems for troubleshooting. In this one I and my colleagues were able to investigate how technicians used an industrial expert system developed from a shell in the standard iterative refinement approach to troubleshoot an actual electro-mechanical device (Roth, Bennett & Woods, 1987).

The original goal was to reduce the technician's skill requirements. A second goal was to provide management with extremely tight control over the technicians who were responsible for troubleshooting the devices.

The expert system was designed to be a stand alone problem solver who would simply output a solution. But, what was the person supposed to do? The person was expected to go to the remote site and dial into the expert system to initiate a run. The machine would then use the person as hands and eyes; the person's role was simply to serve the machine, to collect data, to carry out various kinds of tests, to make observations about device behavior and, finally, to implement the repair selected by the machine expert.

If this model of problem solving was correct, the data that we collected should look like that in Figure 10. The machine expert would direct the technician to perform a series of data gathering activities (observe, measure) until the machine produced a hypothesis and the operator effected the directed repair (e.g., replace the bad part). Essentially, the expectation is a straight, linear execution of the machine's instructions until the solution is found.

How much of the time did this happen? About 20 percent of the time. Almost 80 percent of the time, the protocols looked like the one in Figure 11. The machine generated multiple hypotheses, not a single one. One part of the human role was to filter the machine's solutions, and decide which was really the right one. People had to figure out if the machine was on track; as a result, they had to go through their own diagnostic process. Were the machine generated hypotheses inconsistent with the operator's experience? If so, the operator would need to supervise the machine. But, remember that the machine design provided no mechanism for the technician to direct the machine or to gain access to the knowledge or tools available within the expert system. So the operators tried to adapt and invent ways to interact with the system. Specifically, the operators tried to trick the automatics in order to get the machine to do what needed to be done. In one case, when the machine response did not make any sense, the operator went back a step and tried the opposite answer to see what would happen and if the machine's behavior would be more plausible.

The actual results were that a successful diagnosis required significant technician participation and skill. But, no mechanisms had been provided for the technician to interact with the expert system, other than in trivial ways. No mechanisms were provided for the technician to understand and track the expert system's diagnostic process.

The important thing about this study was that we were able to analyze how the system performed under various unanticipated conditions, such as underspecified instructions. This required judgement, because the technician had to use knowledge of the domain in order to interpret what was really required. Misinterpretations and mis-entry errors also occurred, as well as errors in the knowledge base itself (the machine would sometimes make a mistake due to an incorrect rule in its knowledge base).

Adaptation to special conditions was also a crucial issue. For example, it might not be possible to carry out the expert system's plan, because some assumption behind that plan was not true. For example, a tool was not available to do the requested test or the system assumed a particular device was operable, when, in fact, it was not. And therefore, the test requested by the machine could not be carried out until the device was at least minimally operable.

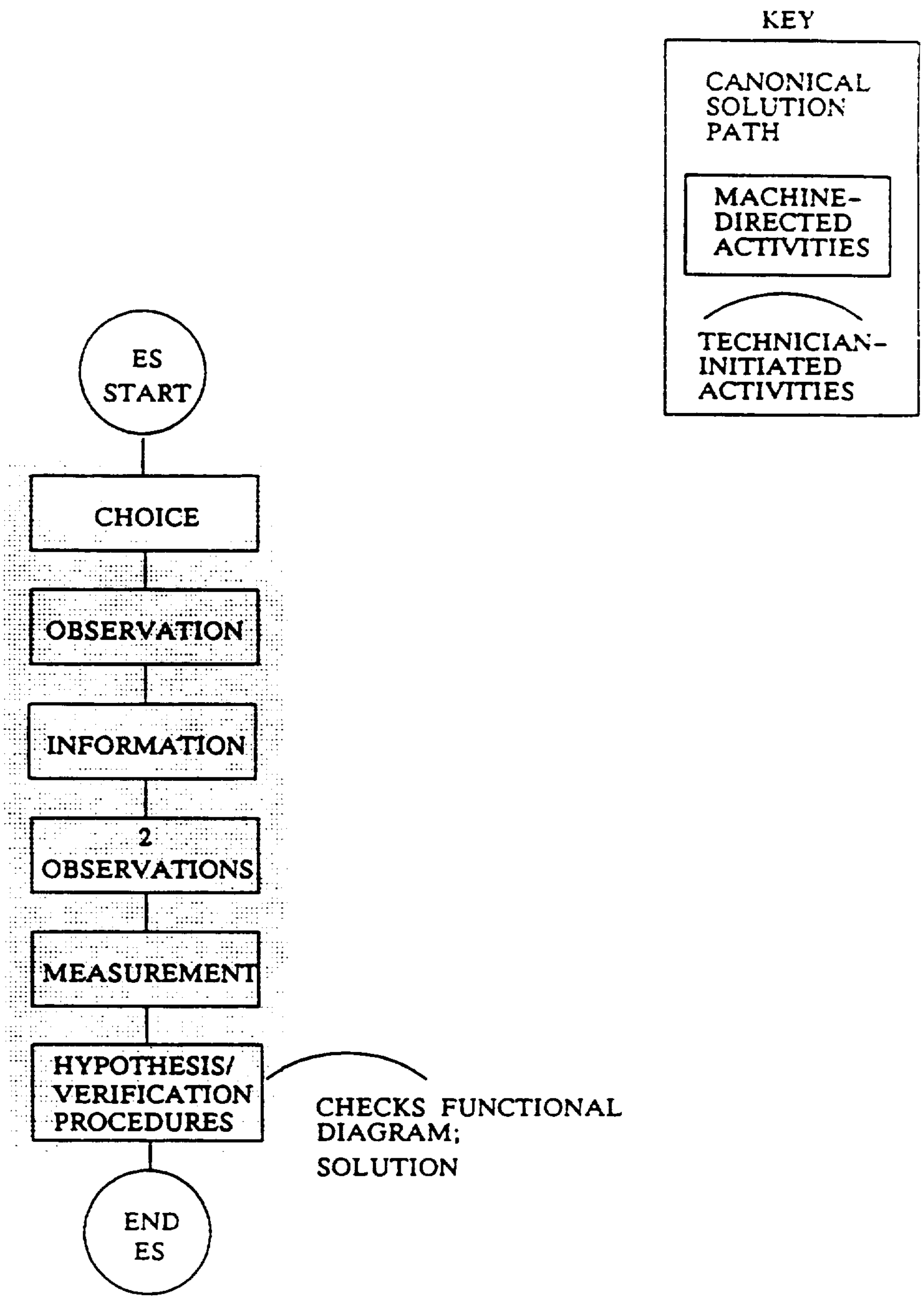
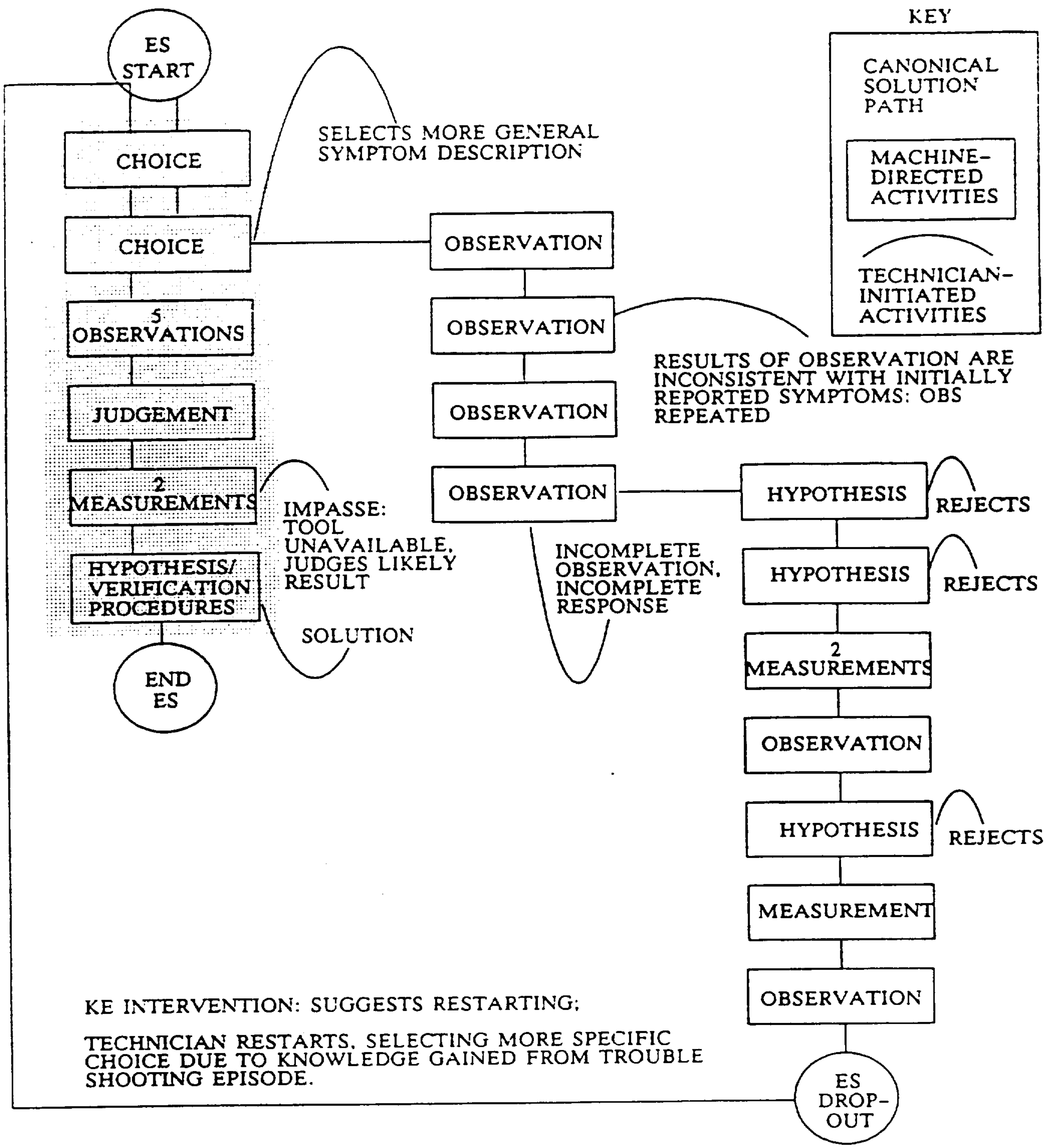

KEY
CANONICAL SOLUTION PATH
MACHINE-DIRECTED ACTIVITIES
TECHNICIAN-INITIATED ACTIVITIES
ES START
CHOICE
OBSERVATION
INFORMATION
2 OBSERVATIONS
MEASUREMENT
HYPOTHESIS/ VERIFICATION PROCEDURES
CHECKS FUNCTIONAL DIAGRAM;
SOLUTION
END ES

Figure 10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2 MEASUREMENTS
HYPOTHESIS/ VERIFICATION PROCEDURES
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SELECTS MORE GENERAL SYMPTOM DESCRIPTION
IMPASSE: TOOL UNAVAILABLE, JUDGES LIKELY RESULT
SOLUTION
OBSERVATION
OBSERVATION
OBSERVATION
OBSERVATION
RESULTS OF OBSERVATION ARE INCONSISTENT WITH INITIALLY REPORTED SYMPTOMS: OBS REPEATED
INCOMPLETE OBSERVATION, INCOMPLETE RESPONSE
HYPOTHESIS
REJECTS
HYPOTHESIS
REJECTS
2 MEASUREMENTS
OBSERVATION
HYPOTHESIS
REJECTS
MEASUREMENT
OBSERVATION
ES DROP-OUT
KE INTERVENTION: SUGGESTS RESTARTING;
TECHNICIAN RESTARTS, SELECTING MORE SPECIFIC CHOICE DUE TO KNOWLEDGE GAINED FROM TROUBLE SHOOTING EPISODE.

Figure 11

In summary (Figure 12) we found that there was a significant role for the operational people in this system. But the expert system, if anything, hindered human diagnosis. It did not even provide a memory trace of all the diagnostic tests that had been run up to that point in time on the system. The operator was functioning without any aid whatsoever, even as simple as a electronic notebook. Yet he was forced to make a parallel, independent diagnosis in order to do the job of supervising and interpreting the information provided by the expert system. Again, the question is not whether the expert system did or did not help; the question is whether there is support for the human's role. In this case, there was none.

Expert Systems for Troubleshooting

original goal: ***reduce technician skill requirements to reduce costs and give management tighter control over technicians***

actual results:

1) ***successful diagnosis required significant technician participation and skill (almost 80% of test cases) due to unanticipated variability***

2) ***no mechanisms were provided for the technician to direct the expert system***

3) ***no mechanisms were provided for the technician to understand or track the expert system's diagnostic process (black box design)***

4) ***some technicians discovered ways to manipulate the expert system***

5) ***technicians who passively followed the instructions of the machine made more execution errors***

6) ***technicians had to perform partial diagnosis on their own without any assistance or information from the expert system***

Figure 12

LESSONS OF TECHNOLOGY CENTERED AUTOMATION

In summary, Figure 13 lists the lessons learned when a technology centered approach to automation is employed. First, the human role in the system is changed in unforeseen ways. However, if the new system supports the new human role, the person will be able to effectively accomplish the task. Second, there is a myth about de-skilling. Sometimes skills are reduced, but in general, skills are changed. The mix of skills, the kinds of people needed to operate a system, change. Third, the critical human role is to adapt to unanticipated variabilities and to amplify the requisite variety in a system. The person is there to help the machine do the job. Finally, new kinds of error forms and new kinds of system breakdown patterns can happen. The frequency and/or relative consequence of an error can be changed, and these new error forms, as well as their consequences and frequencies, need to be examined to be sure that everything has moved in a positive direction.

Lessons of Technology Centered Automation

shifts in automation have changed the human role in system performance in unforeseen ways

de-skilling myth—changed pattern of skills; it does not eliminate human skill

critical human role is to adapt to unanticipated variability

new error forms and types of system breakdowns

Figure 13

We can also summarize the fallacies in automation across cases like those discussed above:

- incomplete automation where the machine is assumed to be fully autonomous when it is semi-autonomous;
- failures to understand and support the human's new or changed role;
- brittle machine performance due to designer's overconfidence bias;
- pseudo-consultants; machine locus of control.

HUMAN CENTERED AUTOMATION

In contrast, Figure 14 summarizes the lessons learned from a human centered automation approach. First, a human locus of control is required. The operator must have effective authority over areas of task responsibility and this cannot be merely lip service authority. The operator must have control of the machine resources including some degree of freedom of action and methods to instruct or direct the lower order machine agents. The machine should always provide support to the human. Designs requiring a choice between fully automatic or fully manual operation must be avoided.

Human Centered Automation

1. human locus of control:

- ***effective authority as well as responsibility***
- ***control of machine resources, i.e., degrees of freedom of action including ways to instruct or direct lower order machine agents***
- ***the machine should always provide support to the human (e.g., avoid cases of forcing the human to chose between doing the task completely by himself or letting the machine do it completely by itself)***

2. human as supervisor:

- ***monitoring of lower order agent***
- ***greater need for high level situation assessment***
- ***human tracking of machine state (what does it know, what is it doing, why is it doing it, what will it do next)***

3. support for error detection and recovery:

- ***communication breakdowns between multiple agents***
- ***use machine intelligence for constraint checking and critiquing***
- ***support human situational awareness***

Figure 14

Second, the general role of the human supervisor in these highly automated systems is to monitor the activities of the lower order agents. This means there is a much greater need for high level situation assessment and new information displays to help accomplish this job. The need for human tracking of what the machine is doing, why it's doing it, and where it's going to go next is also greater. Third, the human role in error detection and recovery needs to be actively supported.

DISCUSSION

Question: Are you saying that automation should not be used at all?

Response: No. As I said at the beginning, the issue I've been working on is not whether or not to use technology. It will be used for a variety of reasons. The question is how is it used. Studies that I've done related to process control, as well as other studies, have all indicated that more leverage can be obtained from technology improvements and that some negative post-conditions or consequences of automation can be avoided if the effect on the human role is taken into account. Support mechanisms must be provided. It is not possible to say, in any absolute sense which is better—automation or lack of it. Rather, it is a question of the choice in level of automation. What post-conditions result for the human's role and how are they supported? The total system performance should improve. The question is not whether the person alone can do a better job than the machine alone. I want the two together to do it better.

Question: What do we have to change? What do we have to do to work around this problem?

Response: We must be able to provide operational people like you with the tools (decision automation technology and information systems) to understand the possible error forms. Can we develop ways to use the technology to provide effective explanations of the basis for a machine-suggested diagnosis? My research and system development program with the process control industry is to provide designers with such tools. My mission today was not to go through these techniques. We do not by any means have all the answers, but we do have some. And I think together we can develop more.

Comment: Some of the major points I learned from this presentation are:

Our pilot training needs to be changed a little bit. We have to spend enough time in teaching the pilot what the designer expected the machine do when he designed it. This may sound like a cliche except that when we trained the pilot, we said, "push this button to go up, push this button to go down," but we have not spent a lot of time teaching how to do this manually, efficiently and safely. We should convince the pilot that the designer of the flight management computer intended the machine to fly the aircraft exactly like the pilot would. If the pilot understood this, then when the machine is about to make a gross error, the pilot would recognize the gross error and be sensitive to the fact that the gross error is about to occur and will be able to correct it.

Another place where our training has to be changed is the machine has to indicate the priority for fault management to the human. In the power plant example, the computer system could have worked if things had been prioritized. In some aviation cases, they are, but in other cases, a laundry list does not help you at all. Now the EICAS system in the 767, for example, is good in some ways and not quite perfect in other ways. A list of yellow messages is fine as long as there are not more than about 4. As soon as there are more than 4, it is difficult to sort them out. To the designer, the answer may be simple—prioritize by indenting the less important ones. The problem is that for the human being, indentation means a subset of the primary set. So that does not work too well either. In fact, we are very vulnerable to EICAS misreading and there needs to be a better method of prioritizing the display.

The last and most critical thing is we have to teach the pilot that it is not a question of either all automatic or all manual. We have to teach him when to interrupt the machine's action in a supervisory manner. It should not be an all or nothing approach but somewhere in between. In other words, the crew may need to eliminate the FMS and use the remote control panel, but they may not need to disconnect everything. That's the direction our teaching must take if we are to help the human interact with the machine.

Comment: Your examples in the banking industry indicated where they used to have problems across the board in the automation area. But these situations have been rectified. It seems to me that the technology has now reached the point where we've got to take the blinders off of the engineers and designers so that they understand that the technology does not stop at the front of the display. The problem is how to display the information. The technology problem goes right to the actual application and that's where all the problems are. Designers were only concerned with how to generate information contained in the computer and how to get it to the controller's CRT. The designers then incorrectly assume that their problem is finished. The controller/pilot must not be left to figure out how to use this information.

Question: Sometimes it's difficult to get a list of examples of what not to do. Do you have a list, even a small list?

Response: Figure 14 is an attempt at this list. A variety of cases would be required to develop a more thorough list, but it should now be possible to put such a list together.

Question: Dave, it seems to me that problems occur in trying to design a totally automatic, safe system. Conversely, success happens when the automation was designed as a tool for the operator. We should stick with this philosophy in the cockpit. It should be designed as a tool for the pilot. Up to this point, I've looked at the FMS as another navigation tool, an extension of what we had in the past. The new systems should not take the place of the pilot and that is the important issue.

Response: I think you're right. The problem researchers and developers like myself have is determining what it means to design the automatic system as a tool for an operator. And I think the down side is that lip service is given for that philosophy. Sometimes it seems as if we're moving along in the right direction when in point of fact, we may be completely undermining the operator's role in the system who may soon be only running alongside the automatics.

Question: Dave, everybody wants guidelines. Do you believe that there will come a time when you can sit down and make up a list of general guidelines?

Response: I think the answer is partially yes, but it would look very different than the traditional human factors guidelines. The problem is that the typical guidelines usually do not relate to the real design process or the work constraints which must be considered. Such guidelines are therefore irrelevant.

Question: The examples you gave here, particularly for banking, illustrated how the automation can lead people astray which at least gets people thinking about it.

Response: That is where guidelines will be useful. They may not be guidelines in the traditional sense, but they are pointers into relevant pieces of the literature. As examples, they function as reminders for designers. For example, something as simple as a computerized meter, a meter on a computer screen, doesn't have to look like an analog instrument. It can have all kinds of interesting features, most of which you rarely see. The designer could use this part of the database to get a long reminder list of issues relevant to his application.

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LUFTHANSA COCKPIT SYSTEMS SURVEY: A-310

Captain Peter H. Heldt
Chief Technical Pilot—Lufthansa

INTRODUCTION

Lufthansa is using cockpit surveys to obtain up-to-date information and feedback from their flight crews as a basis for cockpit specifications.

1976-Survey

In 1976 we conducted a survey of our existing fleet of: B-707, B-727-200, B-737-100, B-747-200, DC10-30 and A300-B2. At that time, development of modern avionic equipment indicated an imminent change in cockpit design. Questions regarding whether and how to continue with further automation on the flight deck were of special interest. The results of that survey were published shortly after introduction of the A310-200 and the B737-200 Adv. Both aircraft have Flight Management Systems (FMSs), a new generation of auto flight systems, and are 2-crew airplanes.

This paper includes data only for the A310-200.

Our A310-200 fleet consisted of thirteen A310-200 airplanes at the time of the survey "snap shot." The A310-300 and A300-600 were not yet delivered. Vertical navigation was only in an introductory stage with so-called OP++ status. Thus questions regarding VNAV could not be included.

The Questionnaire

The questionnaire was anonymous. The only personal data requested were:

Function (CM1 or CM2)
Types of airplanes flown previously
Hours logged on A310.

All questions were to be answered with standardized ratings on a five-point scale with a neutral center position. Free text comments were encouraged. The entire volume of documented written comments represent a valuable source of information for system designers. The questionnaire consisted of two main parts.

Part 1: Cockpit lay-out, general handling qualities and airplane systems

Part 2: Electronic crew interfaces: ECAM, EFIS, AFS, FMS

Part 2 was subdivided into the following four main topic areas according to a standard man-machine interface model:

I. Physical Interface (reach and see)—control location, reach and handling, display location, readability, color and lighting, etc.

II. Interface Dialogue or Operational Considerations (understanding)—Ease of understanding of operational rules, display rules, interlocks, and amount and kind of required training.

III. Interface Tools (usability)—General usefulness, adequateness and importance of features.

IV. Organizational Aspects of the interface (appropriateness in the operational environment)—Factors like reliability, logistics, ATC-constraints, etc.

Some Statistics

Total number of questions per questionnaire = 654
Number of questionnaires distributed = 202
Number of questionnaires returned = 121 (60%)

ECAM (ELECTRONIC CENTRALIZED AIRCRAFT MONITORING)

General Observations

Pilots with more than 500 hrs on the A310 gave more positive ratings than those with less than 500 hrs.

Physical Interface (Reach and See)

Generally, the physical interface was judged positively. The new visual display units are welcomed. Only a few aspects were criticized:

Contrast and Brightness

Contrast and brightness of the displays were judged as inadequate under daylight conditions. CRT surfaces often are contaminated by dust and fingerprints. Display wiping and cleaning is a common preflight procedure.

Interface Dialogue (Understanding the ECAM)

Automatic sequencing, display rules, and readability all received positive ratings. However, the aural warnings were mentioned as being too loud. All pilots attest to their effectiveness as "attention catchers," but the comments of the pilots differ regarding the issue of direct failure recognition via specific tones. Sixty-four percent of the pilots state that the present number of different aural warnings is "just right." (The A310 has 7 aurals plus voice warning. The A300-B2/B4 had 13 aurals + voice, which received a clear "overdone" in our 1976 survey).

Learning to operate and understand the ECAM does not seem to represent a problem during normal operation.

Interface Tools/Support of the ECAM

The principle of computer-aided guidance during normal and abnormal operations is generally welcomed. The general ECAM performance to cope with system faults is judged to be of value by 87% of the pilots. The system displays are judged to be important or very important by 97%, while only 21% of the pilots find the dedicated warning light display panel (WLDP) of any value.

This favorable overall rating however, also includes some comments regarding ECAM's weaker elements: Checklists offered by ECAM received mixed ratings. The comments mainly center on the idea that the checklist design sticks too much to the 3-crew basic A300-B2/B4, i.e., the procedures involved to operate the aircraft systems are basically unchanged. Pilot actions are sensed by push-buttons, and this calls for some additional activity ("monkey switching").

Because of limited redundancy and computer capacity the ECAM system requires the pilot to change from screen to paper checklists and vice versa. This is perceived as being confusing. 99% of the pilots state that thorough training is required to handle this aspect.

Generally, pilots felt that proficiency in dealing with abnormal situations cannot be achieved during line operation. Therefore, they uniformly called for more simulator or refresher training.

Organizational Interface (Fit into the Environment)

The survey results showed that reliability, maintenance and logistics do not seem to represent any problems. Ninety-Five percent of the pilots indicated that they have never or have seldom seen an ECAM failure, nor did they have difficulties in getting spares when needed.

Many pilots claim that the cruise phase, where most T/O-inhibits are cancelled, begins too early (1,000 ft/GND). In dense traffic areas the crew is still busy with departure procedures.

EFIS (ELECTRONIC FLIGHT INSTRUMENT SYSTEM)

General Observations

As with the ECAM more positive ratings were assigned to the questions by crews with more than 500 hrs. flight time.

Physical Interface (Reach and See)

Again, these interface aspects were judged overall very positive. Changing personal instrument scanning technique from electro-mechanical instruments to CRT-displays seemed to present no problem. The following minor complaints should be considered:

- Vision and cross cockpit readability of LCDs for decision height and flight path vector is reported to be only marginal.
- The location of the navigation display (ND) which is obstructed by the control column is not optimal.
- The quality of the artificial voice for radar height is rated as good or very good by 94% of the respondents, but our pilots state that it is too loud.
- As with the ECAM, the EFIS displays require frequent cleaning to reduce any dust or reflection which is reported to be annoying during daylight operation.

Operational Interface
(Understanding EFIS Display Formats)

- Our pilot ratings substantiate that these new visual display units are superior to electro-mechanical flight instruments and are self-explanatory (intuitive) to a large extent.

- The detailed speed scale obtained an excellent rating; 94% said it is advantageous.

- The display of preselected altitude in the primary flight director (PFD), which is just a duplicate of the glareshield selection, triggered a request for a "full blown" PFD presenting all "basic T" data.

- The indication of radar height in the PFD consists of a plain numerical readout, but is supported by artificial voice. Eighty-three percent of the pilots confirm that their awareness of radar height and rate of descent is satisfactory. This implies that aural signalling for essential flight parameters is adequate and acceptable.

- On the other hand, presentation of drift angle is flawed: 71% say it is poor or very poor.

- Pilots did not report encountering any problems with EFIS during training. Line and simulator training are considered most efficient and valuable, while using the airplane operations manual (AOM) is considered less efficient.

The EFIS as a Tool (Support of the Pilot)

Again EFIS are generally accepted. Some details should be mentioned:

- The design of the speed scale again received high marks.

- 95% of the pilots say that their speed awareness is helped.

- The standby airspeed indicator is thought to be rarely used for reference.

- The flight path vector (FPV) received less approval. This new display element needs further development. Some pilots want a FPV with flight director (F/D) commands.

- Among the various ND Modes, the MAP Mode is judged to be the most important one, followed (by a considerable distance) by the PLAN, ROSE and ARC mode. 90% of the pilots state that the ND-CRT-display is an eye-catcher.

AUTOFLIGHT SYSTEM

Physical Interface (Reach and See)

The similarity of the FCU control knobs in the glareshield encourages errors. Twenty percent of our respondents mentioned that the knobs are to indistinguishable from one another, particularly due to their close physical proximity, thus this design is likely to induce mistakes. A typical comment states: "all in a row look pretty good, but it takes time to identify."

The legibility of the labels is good under daylight conditions; at night, legibility is impaired. Lighting level of different panels is not synchronized. A lot of comments criticize the PRESET SPD/MACH indication and label.

Dust behind the glass window of LCDs hampers readability.

Eighty percent of respondents find it important that most FCU parameters are repeated in the PFD and ND or are summarized as flight mode annunciation (FMA). However, 51% report having missed a repetition of the vertical speed (V/S) value and the SPD/Mach value in the PFD.

AFS Operational Interface (How to Use It)

The multiple functions for the SPD knob seem to be acceptable. This does not hold for the altitude selector (30% critical reports). Whenever rotary push/pull knobs or simple push-buttons are intended to perform the same function, push-buttons are preferred.

There are a variety of comments on the preset/SPD/Mach function and its readability:

- The preset function is required but actually operating the button was judged to be too difficult.

- The rotary knob for the V/S is strongly criticized by 47%. Occasionally the knob is turned in the wrong direction.

- 42% have experienced inadvertent changes of dialed selections when operating the selector knobs. Some comments mention that this is the reason why push-buttons are preferred for "engage" functions.

- The information of the FMA in the PFD regarding color, quantity and arrangement seems to be highly appreciated.

- 74% of the crews use 100% of all AFS functions. Every second copilot indicates a desire for additional functions. Captains seem just happy with the modes provided.

- There is a common request for a "*" symbol for speed and altitude in profile mode in order to see what the A/P is going to do next. Crews report that throttle movement often is the only cue they have to know that a mode change has occurred.

- Line training (learning by doing) is regarded as the best means of instruction for the AFS, according to 83% of respondents. The simulator is accepted by 1/3. The AOM is used by only 19%, whereas 49% consider manuals a poor training method, and 30% report never using the book.

<u>AFS as a Tool in Daily Operation</u>
<u>(How Well Can a Task be Performed)</u>

The number of modes for lateral, vertical navigation and thrust control are considered adequate by 83% of the respondents.

<u>Use of the AFS</u>

<u>T/O:</u> 75% use AFS (thrust only) plus FMS in NAV + profile (PROF). 11% report performing the T/O manually with FD.

<u>Climb:</u> 91% report using all features, only a small group reports flying manually.

<u>Cruise:</u> AFS is uniformly reported to be used almost 100% of the time.

Descent: No uniformity here, although the largest group uses AFS + FMS in NAV. Profile descent speed is reported to often be too slow for ATC requirements.

Approach: 55% report flying the approach manually with ILS. Non-precision approach is flown manually (39%). Others report using AFS+FMS in NAV. Visual approaches are flown manually without FD (78%).

Landing: Landings are performed manually by 95%; control wheel steering (CWS) is reported to be almost never used.

The guidance quality of the AFS in lateral modes is judged to be accurate, but in LAND mode the ILS capture of the system is criticized. Comments report overshoots when capturing. Also, during altitude capture, oscillations are reported to occur. Throttle-movement is judged as too active during certain flight phases.

Comments also note that synchronization of both engines by the auto throttle system should perform better.

The AFS is sometimes switched off for passenger comfort reasons.

Organizational Interface: (Fit into the Environment)

Eighty-five percent of respondents feel that ATC requirements can be met with the present system. Seventy percent indicated they rarely encountered missing functions due to lack of spares or maintenance problems.

- CAT III is reported to almost never be impaired by AFS malfunctions.

FLIGHT MANAGEMENT SYSTEM (FMS)

Physical Interface: (Reach and See)

- Cross cockpit reach of the opposite CDU is reported as an inconvenience.
- Readability of the keyboard is judged to be good under daylight conditions but poor during night flight (53%), due to dimming performance.

- Size of the keyboard is criticized by 1/6 of the pilots.
- The arrangement of the keys is accepted by the pilot group with more than 500 hrs. False inputs reportedly do occur however (keys are too close to each other).
- The parallax of the "line select" keys fosters inadvertent inputs.
- 22% judge the FMS CRT as too small and too overloaded to locate the desired information quickly (graveyard of numbers).
- 65% ask for a color display.

Operational Interface: (Working with the FMS)

- The FMS menu structure and the scratch pad operation is much liked.
- Rigid input format rules frequently produce "incorrect data" messages.
- As is the case with the AFS, learning by doing seems to be an applicable principle for the FMS.

FMS as a Tool

- Pilots report that in some situations it is difficult to find specific data quickly, (although these situations are relatively rare). Typical cases are: return to departure, route change, or waypoint change.
- The response time or computational performance of the FMS is judged to be far too slow.
- Lateral Nav is judged outstanding while the available vertical NAV is just average (note: no profile (PROF) existed in 1986).
- Due to overall satisfaction with the FMS, aircraft control is generally delegated to the FMS or FCU. During approach and landing phase, the FCU is preferred in order to stay head up.
- Inputting navaids which are not in the current database and entering waypoints via the scratch-pad is judged to be workable without undue hardship.

- Bearing/distance to a waypoint is judged highly important.
- SEC FPL (secondary flight plan) is judged important by 78% of respondents.
- Misaligned maps occasionally occur and are annoying when they do happen.

The following additional items are strongly desired features (should be given high priority):

display of minimum safe altitudes,
engine out departure procedures,
airport layout.

CONCLUSIONS

Overall, our pilots like automation. However, flying with the automatics must be as good or better than flying manually. Some problems do occur with automation. "Keeping the pilot in the loop" is a mandatory requirement for any automated function. FMS and ECAM are both well liked. However, both systems are not yet optimally designed. Initial development of the FMS was promoted and tested by a relatively small group of pilots. Further development should be based on a broad (international) range of airline experience. Advanced flight management systems must incorporate an improved crew interface, higher computational performance, and a better fit to the ATC-environment.

WORKING GROUP

REPORTS

Flight Deck Automation: Promises and Realities
Final Report of the Working Group on
AUTOMATION AND AIR-GROUND COMMUNICATION

Compiled by Renate Roske-Hofstrand

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INTRODUCTION

This report is based on discussions held at the NASA-Industry workshop entitled, Cockpit Automation: Promises and Realities, held in August 1988 at the Carmel Valley Inn, California. Several themes emerged during the working group meetings. Among the main themes are:

1) Because controllers and pilots cooperate to achieve safe, orderly, and expeditious traffic flows through the National Airspace System (NAS), designers of automated systems must consider the tasks and goals of both the pilot and the controller.

2) The primary domain for air-ground communication involves navigation on the pilot's side and traffic flow management on the controller's side. Flexible, well designed communication interfaces must be developed where sharing of information between controller and pilot is easily accomplished without increasing workload levels.

3) Cockpit automation development must evolve so as to achieve compatibility with the NAS efficiency goals which relate to increasing traffic density in available airspace. Cockpit situation management must be matched to the traffic flow management concerns of the controller.

It should also be noted that the air/ground working group was tasked with discussing some of the current issues in air/ground communication and therefore a conscious effort was made to avoid any detailed discussion of topics explicitly related to future planned datalink technology during this workshop. The overwhelming feeling of the working group members, however, was that it is in the context of these future systems where new approaches to design are called for and can be of most benefit. A follow-up workshop on these issues was suggested. In fact, it is anticipated that the interdependencies noted below between pilot and controller tasks will be even more closely coupled in the future and will likely include other ground-based elements such as airline dispatch interfaces and/or airline maintenance operations.

TOWARDS COORDINATED DEVELOPMENT AND DESIGN

The goals of automation in both the cockpit and control room environment have traditionally been defined in isolation from one another. Because these environments both function within the NAS, there exist strong interdependencies which need to be taken into account in the definition and design of automation tools for both pilots and controllers.

The interface between pilot and controller primarily supports communication activities regarding an aircraft's safe progress through airspace populated with many other aircraft. A high degree of cooperation between pilots and controllers and adherence to commonly understood (standard) procedures is the foundation for current safe operations.

It is important, however, to realize that the specific task goals of the pilot and the controller differ in the following way: Pilots are in command of their aircraft only. They are concerned with navigating through traffic and weather in their immediate vicinity. Therefore, pilots can be said to be single-aircraft centered in their tasks and goals.

Air traffic controllers, on the other hand, support the pilot's task of safe navigation but share their attentional resources among all aircraft in a given sector for which they carry responsibility. Controllers are increasingly concerned with system-wide efficiency as it relates to traffic throughput and total number of aircraft served. Controllers can be said to be multiple-aircraft centered or "distributed" in their tasks and goals.

How does one then appropriately shape and coordinate the development of automation tools in this interdependent context? Cockpit automation development must be able to specify what the consequences of a particular interface design are with respect to both the pilot's tasks and the controller's tasks within the operational backdrop of the overall system.

SYSTEM-WIDE CONSEQUENCES OF COCKPIT AUTOMATION

The advent of automation in the cockpit (i.e., Flight Management Computers, global navigation systems, sophisticated autopilots, etc.) assists pilots in complying with standardized procedures and controller requests. With automated on-board navigation equipment complex navigation and route structures can be adhered to more precisely (as long as no unforeseen changes occur). Conceptually, at least, the advent of cockpit automation should be beneficial to controllers as well as to pilots.

Automated navigation usually results in more precision and predictability of an aircraft's position in the available airspace since maneuvers are executed automatically and do not incur the common costs of pilot response or deviation from prescribed routes or altitudes. Additionally, complex route structures with many constraints (minimum or maximum altitudes or even time limits) present no additional burden on the pilot, because they are executed by the on-board computers.

If aircraft, because of their cockpit avionics, can adhere more reliably to complex navigation structures, then controllers could have more flexibility in using such structures and issuing clearances accordingly. Furthermore, controllers, in addition to having a larger repertoire of possible alternative routes available, can expect more consistent adherence to their instructions. A controller's expectation about the possible range of deviations from the issued clearances is positively affected, i.e., possible flight path deviations are minimized since navigation is automated. This reduces the need for the controller to re-check and continuously monitor an individual aircraft's progress since he/she can rely more strongly on the execution of a particular flight path over time when dealing with an "automated" aircraft.

Cockpit design at present occurs in isolation from the larger system context. For example, the fact that controllers now have no explicit information available to them regarding the type of automation equipment available on a particular aircraft precludes their ability to make strategic use of this information. In other words, the benefits of cockpit automation cannot be fully realized for the system as a whole. A question that needs to be considered in this context is the following: Should a controller's strategy for dealing with traffic consider the equipment available on board the aircraft? Undoubtedly the answer for the future must be affirmative, i.e., the pattern of control and cooperation between pilot and controller must evolve from common, basic assumptions about an aircraft's capabilities.

TRADEOFFS: PILOT VERSUS CONTROLLER CONCERNS

Flexibility in route assignments is necessary to move aircraft safely and efficiently through the available airspace. A heightened emphasis on traffic "throughput" makes strategic flexibility in traffic control a necessity. Pilots currently perceive increased effects of the NAS demands primarily as increased workload in the flight phases occurring in terminal areas. To a large degree this occurs because of poor interface design. Pilots in high density traffic areas must be able to respond quickly to changes in ATC clearances. Older technology aircraft fare better under these circumstances, presumably because the pilots themselves are processing and integrating rapid changes in ATC clearances, and they do not need to engage in the extensive re-programming efforts now required to keep the on-board systems of the "advanced cockpits" informed of these changes. Thus pilots of non-automated aircraft do not experience a noticeable increase in the level of workload as a result of ATC instructions.

This paradox is also in part a direct result of control policies that deny controllers the use of different control strategies for automated aircraft. The mixed traffic is presently dealt with as if there were no performance differences among the differently equipped aircraft. While cockpit automation should allow for more flexible controller strategies in order to meet the ever increasing capacity demands in addition to reducing the pilots workload during critical flight phases, just the opposite occurs. Pilots of "equipped" aircraft experience increased workload levels as a result of changes in controller issued clearances.

There exists, at present, a tradeoff between overall NAS efficiency, i.e., flexibility of control strategies, and the pilot's ability to accommodate this flexibility in the automated cockpit. The potential benefits of cockpit automation are clearly compromised by the seemingly sluggish and isolated (from cockpit automation development) air traffic control system. The solution to this state of affairs rests with a joint commitment by airframe and avionics manufacturers, air carriers and the FAA to develop air/ground automation tools that are *explicitly* designed to be compatible with each other.

DIRECTIONS FOR RESEARCH IN INTERFACE DESIGN

Among the specific complaints of pilots with respect to air/ground coordination are the lack of adequate electronic map displays. The anecdotal evidence presented at the working group points at both, an inadequate database in terms of completeness, and at the inadequate current format of the interface to the database.

The entire concept of an "image assisted communication system" seems to have eluded designers of current advanced cockpit systems. When the controller issues clearances the pilot should not have to resort to paper charts to follow the instructions. The electronic map display should be able to allow the pilot to easily locate unpublished temporary fixes and provide an interface with which controller-issued clearances for route structures can be stored and followed easily.

Questions of maintenance and integrity of the navigation database need to be addressed. The potential benefits of a common pilot/controller geographical navigation database should be explored and evaluated. Development towards these jointly considered automation systems should be evaluated against the following guidelines:

1) All aircraft in a given airspace can operate efficiently i.e., in a safe, orderly, and expeditious manner.

2) The controller can maintain a high degree of confidence that an aircraft will follow issued instructions.

3) The pilot has available suitable information displays to comply with controller-issued instructions.

4) All humans in the system are comfortable with resulting work-load levels.

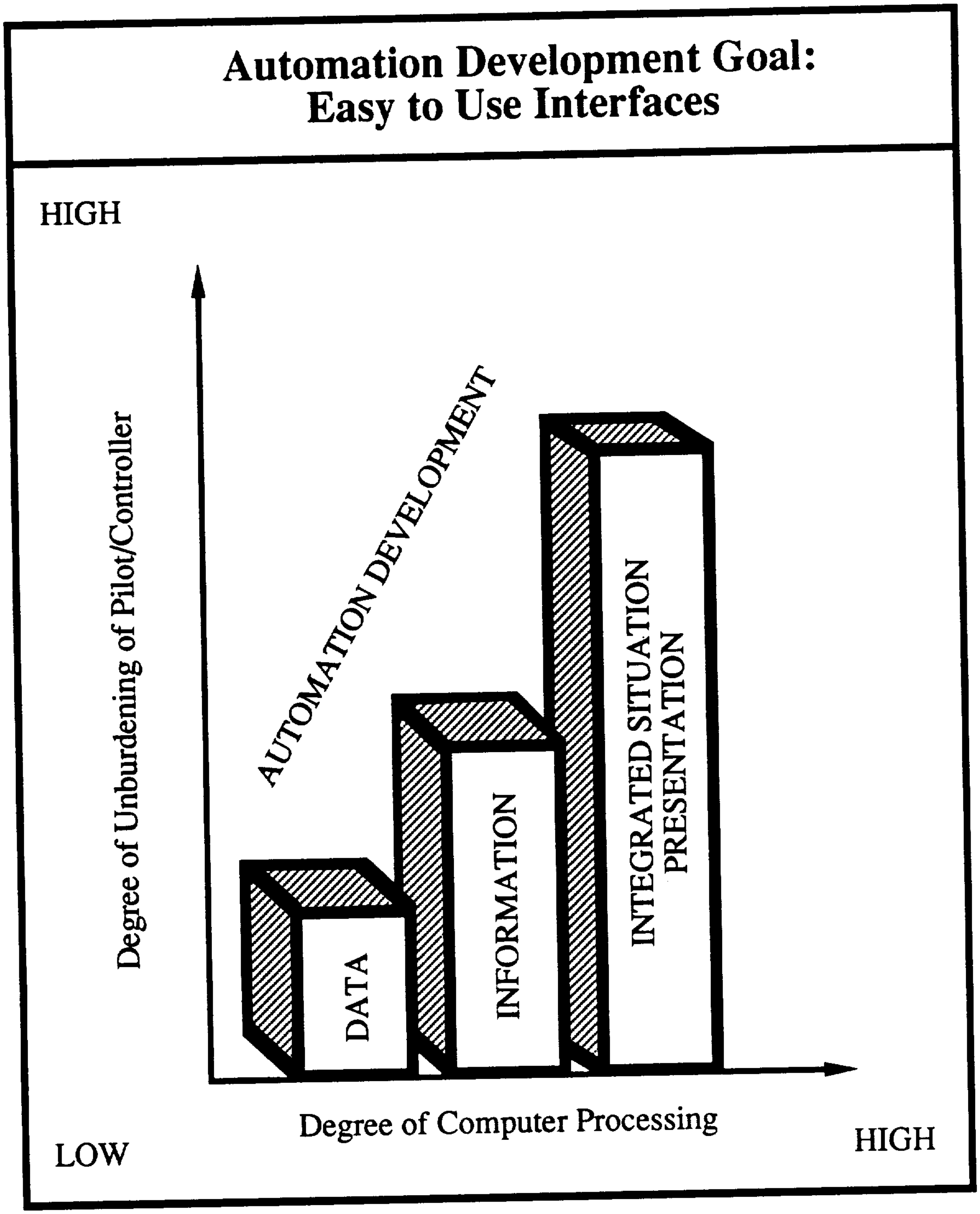
5) Cooperation between pilots, controllers, and dispatchers is encouraged and enhanced via easy to use, image-assisted communication interfaces.

SUMMARY

Some major issues discussed by the working group are summarized in Figures 1 and 2. Figure 1 illustrates the coupling of computer processing and ease of using the data. Figure 2 is a diagram of the information flow in a shared environment. The exchange of information via voice-link, or in the future data link, is most critical.

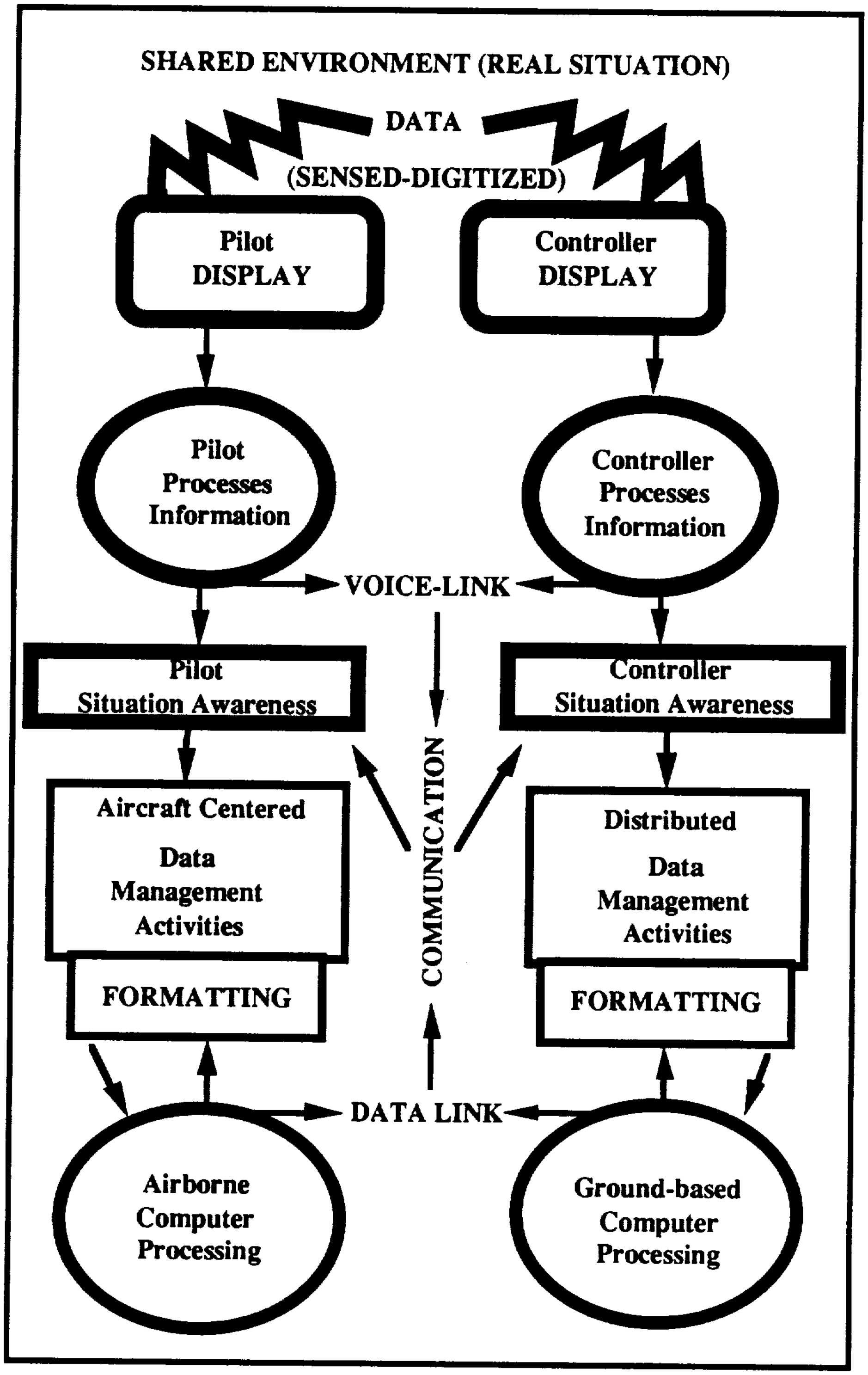
Operational safety and efficiency goals demand full and adequate situation awareness from both the pilot and the controller. While pilots are single-aircraft centered in their tasks and goals, the controller's attention is distributed over multiple aircraft. Hence there exist different needs which must be accommodated by the interface, i.e., the joint concern for an aircraft's safe navigation must be supported by features in the interface which are designed to support mutual understanding and effective communication. The inherent trade-offs between pilot and controller goals must be recognized and explicitly addressed.

Designers must specify the consequences of their design decisions in terms of the communication interface between the aircraft and ground-based air traffic control. Future displays for the controller need to include information regarding the "automation status" of an aircraft and prediction functions for traffic paths which allow him or her early conflict resolution planning. Well-designed displays for the pilot must include easy to manipulate and easy to comprehend information regarding area navigation and descent profiles, possibly including superimposed, integrated weather information. Additionally, on the same display, the pilot could be shown traffic that is directly relevant to his aircraft's flight path. The overriding goal for the design of controller and pilot displays must be a shared frame of reference for air/ground communication based on common geographical databases which permit a high degree of cooperation towards meeting NAS efficiency goals.



Automation and Air-Ground Communication Working Group
Carmel, CA; August 1988

Figure 1



Automation and Air-Ground Communication Working Group
Carmel, CA; August 1988

Figure 2

Flight Deck Automation: Promises and Realities
Final Report of the Working Group on
CREW COORDINATION

Chair: Al Ogden, United Airlines
Vice Chair: Barbara G. Kanki, NASA-Ames
Members: Renwick Curry, Tycho Systems, Inc.
Kenneth Malchow, Eastern Airlines
John Wilson, Air Line Pilots Association

INTRODUCTION

The design and implementation of increasingly automated systems on the flight deck raises a variety of potential human factors issues relating to the work that individual crewmembers perform. In addition to these concerns, however, there are issues which affect the crew as a whole; that is, the way in which crewmembers coordinate their activities together. The most obvious, direct effects include changes in task structure, changes in the interpersonal aspects of traditional and standard procedures, and changes in information flow and communication channels.

There are also indirect effects (i.e., effects which are less specifically tied to flying the aircraft). These include changes in the organizational structure of the crew which can potentially create shifts in authority and the redistribution of responsibilities. Whether company policies and training programs mirror such changes is a further consideration. Finally, there are indirect effects which are related to the problems of transition from one technology to another, such as the fact that proficiency must be maintained in manual backup systems in addition to partially- and fully-operating automated systems.

The direct and indirect effects of automation listed above structured the working group discussion of major issues, but once the issues were brought to bear on specific operations, an immediate decision was made to discuss normal and irregular operations separately. Because problems and the strategies used to cope with each are quite different, we also generated separate recommendations.

NORMAL OPERATIONS

Effects of Automation on Task Structure

In considering task changes from non-automated to automated systems (types of tasks, distribution of workload, prioritization in normal operations), we first broke tasks down into Pilot-Flying (PF) vs. Pilot-Not-Flying (PNF) roles. We did not feel that the Captain (CA) and First Officer (FO) roles and responsibilities had been altered, but that the PF/PNF task structure had changed considerably.

In general, in the automated cockpit, the PF (regardless of whether this is the Captain or First Officer) has less direct control of the flight path, though potentially more precise control, and must assume a greater managerial function. The PNF who previously provided PF backup by waiting much of the time, and talking to air traffic control (ATC), has become a more integral part of the PF's flight control duties. In more automated systems, the PNF must provide a type of backup which requires greater active participation in flight control and less systems monitoring. In particular, flight path control is filtered through a communication chain that involves both verbal and digital control display unit (CDU) inputs. For example, one carrier's procedure for a simple altitude change requires both PF and PNF participation; PF to command a CDU entry, and PNF to change the altitude setting input into the flight management system (FMS). The airplane climbs or descends appropriately or inappropriately and both pilots must observe carefully in order to avoid gross errors of reception or data entry.

> *Systems operations*: Largely a non-problematic area, the changes in systems operations include a shift to more passive monitoring (normal operations only); hence a decrease in workload related to monitoring and control of subsystems. Although error messages via electronic crew alerting devices such as the engine indicating and crew alerting system (EICAS in the B757/B767) may occasionally be an annoyance, these are not major problems in normal operations.
>
> *Primary flight control:* A great number of changes are associated with primary flight control, and these issues will be discussed separately from navigational issues. Many flight path functions, such as horizontal path control, are non-problematic, particularly in low workload phases such as cruise. Vertical path control, however, is affected both positively and negatively. Unfortunately, the times of greatest benefit (airport traffic area and other high workload phases) are also the times when some of the negative effects emerge. For instance, ATC can issue a directive that makes vertical path adjustment

necessary. Although FMS operations, in general, create less of a demand on mental arithmetic, vertical path adjustment can be more difficult simply because of the laborious CDU data entry required of a time-pressured PNF. In addition, feedback regarding these adjustments can be frustrating because control is less direct than in manual systems. A computerized system is more unpredictable simply because response time may be slow or variable.

Thus, in spite of the fact that the FMS can provide greater vertical path precision (previous systems did not provide vertical navigational capability), more advance planning is necessary and greater PF/PNF coordination is required due to the possibilities of unanticipated changes. In addition, the vertical path display can have a mesmerizing effect on both pilots distracting them from other flight duties and forcing their eyes inside. Frequently this occurs at a time when extra external vigilance is required during climbs and descents. This may increase the risk of mid-air collision. Whether by command, standard operating procedures, or simply planning ahead, the PF must therefore assume a greater managerial role in order to ensure smooth PF/PNF teamwork.

Less direct control of flight path operations also creates a need for a different type of cross-checking and monitoring. Error analysis can no longer rely primarily on immediate feedback via motor skills; rather, as in the case of cross-checking CDU data entry, and "reading" the mode control display, checking and monitoring procedures increase cognitive workload.

Navigation systems. Similar to flight path control, navigation systems operation has, in general, benefited from increased automation. Enroute navigation radio tuning has largely become a flight preparation data entry activity, relieving both pilots of some degree of inflight workload. Specifically, the entire route is entered into the flight management computer on the ground, and the computer automatically tunes each radio enroute, permitting precise lateral flight path control. No further pilot action is required. However, the benefits degrade when flight plan changes are required, and these cases will be considered in the Irregular Operations section to follow. We are again mindful of the irony, that the greatest benefit of automated navigational parameters occur in the terminal area and this is very often the area in which flight plan changes are requested by ATC.* Finally, it should be noted once again that monitoring tasks are

* Negative effects involving ATC are not intended to focus on flight deck automation problems exclusively. The fact that ATC procedures are not compatible with the newer automated systems on the flight deck is an important but separate issue (see Working Group report: Air-Ground Communications).

affected. Because much of the flight planning can be accomplished prior to flight, there may be a decrease in situation (geographic) awareness, if monitoring is not suitably adapted to this change in task location.

Checklists. More highly automated systems operations in conjunction with EICAS-type messages have allowed many of the routine checklist procedures to become more efficient (e.g., dark cockpit design where "no lights" means "no problem"). Two important benefits were discussed: (1) Checklists may be shorter; therefore, each item takes on increased significance and (2) it is possible to shift the items found on the "moving" checklist (checklist performed while the aircraft is in motion) to a "stationary" checklist (performed while standing still) which is a definite safety benefit. In support of the sterile cockpit concept, the elimination of unnecessary communication during taxi prior to take-off may be an important deterrent to runway incursions.

Flight deck communication: Automated systems have changed the typical communication patterns within the cockpit in a variety of ways. First, as mentioned above with regard to checklists, electronic crew alerting devices such as EICAS have benefited the sterile cockpit concept because communication during this critical time has been minimized and therefore made more meaningful. Another clear benefit to crew coordination is that increased communication between pilots is required for error-free flight path control. Because both pilots participate in operating the FMS, greater communication, hence greater awareness of the planned flight path results.

A more subtle example of how automation affects communication relates to the availability of information for both pilots. There is no question that the new automated graphic displays greatly increase flight deck information resources. It is also generally the case that these displays are equally available to both pilots. Given this situation, there is theoretically less need to share information by means of face-to-face communication. On the other hand, the availability of information does not automatically imply that both pilots are always attending to the same data, although it is tempting to ASSUME that they are. Thus, communication may seem to be redundant at times. However, there are also times when a false assumption would not be tolerable. For example, when mode changes are made, the mode control panel (MCP) is equally visible to both pilots. However, because we would not want to falsely assume that all changes were noticed, mode changes should be announced in spite of the fact that this might be viewed as redundant communication. Verification of mode changes might be alternatively solved by the addition of an annunciator signal on the attitude direction indicator (ADI) itself.

In short, automated systems do eliminate the need for some types of face-to-face communication and this can be beneficial. However, there are other times when communication may seem to be redundant but it would be incorrect and unsafe to make that assumption. Certainly in some situations, the possibility of error would be unacceptable and the formalized sharing of information may be warranted, as well as increased cross-checking procedures. For example, setting the mode control panel inputs to permit descent away from the altitude window setting is particularly dangerous since it can result in controlled flight into terrain. Operation in split mode during descent presents a situation where autopilot altitude capture engaged with autothrottles disengaged could result in a stall.

Summary of Task Structure Changes

- Decreased mental arithmetic
- More cognitive, less motor skill
- Less active systems monitoring
- Increased cross-check workload
- More evenly distributed workload PF/PNF
- More flight path control coordination (formalized crew coordination)
- PF more managerial function
- PNF has increased CDU flight control participation but less systems monitoring

Cultural Changes

Again, we wish to reiterate that Captain (CA) and First Officer (FO) responsibilities have not changed; that is, the Captain still holds the final authority and responsibility.

However, the FO as PNF is now in control of more information than formerly and the CA must modify his/her team management to accommodate to this change. There are two major areas which should be addressed.

> *Redistribution of responsibility for traditional tasks:* First, insofar as the tasks for PF and PNF are redistributed more evenly, task allocation should reflect these changes. More important, both Captain and First Officer must be equally proficient in handling the increased PNF responsibilities. In particular, both pilots must be well-practiced in all areas of automated systems operations; from handling the entry and operations of ACARS data to CDU entry in making flight plan changes, navigational changes and vertical path modifications.

Direction of information flow: In less automated aircraft, crew members were frequently able to accomplish their tasks independently. Given the greater coordination necessary to operate the FMS, however, lines of communication are created which represent a different flow of control. (Note again that this refers to a change in the transfer of information, NOT a change in authority structure.) For example, when CA is the PF, a simplified conceptualization of the flow of information follows [CA → FO → machine], where flight path control is being accomplished through the FMS and affected by CDU data entry. However, when the CA is PNF, the reverse is true: [FO → CA → machine]. Since this sequence must flow in both directions, this reverses the traditional system in which the unilateral direction [CA → FO], or simply CA and FO working independently was more common. It is important that manuals and procedures reflect these changes and that the PF/PNF terminology is supported in conjunction with the CA/FO role distinctions.

Summary of Cultural Changes

- More even division of responsibility between PF/PNF
- "Role reversal" in terms of information flow
- Increased responsibility of PNF

Recommendations for Normal Operations

- Training to address workload distribution
- Formalized crew coordination
- Formalized FMC checking process
- Design changes to minimize entry errors
- Procedures design to follow cockpit design
- Use of plan-ahead procedures (take advantage of automation)

IRREGULAR OPERATIONS

It became clear to our working group, in the course of discussion, that none of the negative effects was really very serious in normal operations. Rather, increased automation on the flight deck has been successful in reducing workload, increasing the amount of informational resources available, and permitting greater precision in several technical performance areas.

Areas of concern emerged only when normal operations were interrupted or no longer possible. Since some of these times occur fairly frequently and are not "abnormal" in terms of malfunction, we defined "irregular operations" as unanticipated deviation from intended operations with respect to a range of possible events. At the least extreme end of the range, irregular operations could be instigated by internal events such as minor system malfunctions or external events such as unusual ATC requests or new weather conditions. At the high end of the range, irregular operations would be brought on by hard failures which prescribe the use of formalized, written procedures (e.g., loss of pressurization or AC power).

Minimum equipment lists: The purpose of minimum equipment lists (MELs) has not changed in more highly automated aircraft. However, the criteria for designing MELs now need to consider the implications of degraded automated capabilities. When irregular operations require a decreasing shift from a fully-operating automated system, there is an accompanying shift in workload and task structure which must be relieved by the appropriate level of resources designated by the MELs.

Task structure: At the onset of "irregular operations," the degree to which tasks must be reassigned will depend on the severity of the problem and the degree to which the automated systems will need to be shut down. In almost all cases, however, the PNF will change from being a passive systems monitor to an active systems controller. Other task reassignments would need to be based on the particular "irregularity" although there should be pre-determined rules (supported by company policy and training) that provide guidelines for switching from a fully operating automated system to a partial system or a total reversion to manual control. It was felt in general, that (1) there should be no arbitrary reversion and (2) the highest level of automation should be maintained, where possible, consistent with safety and tasks required. For example, because vertical path constraints and manual approach building are not in the database, these operations in a completely automated system result in an increase in the number of tasks and workload and such an increase might not be tolerable during "irregular operations." These kinds of considerations must be weighed in selecting the level of automation that can be realistically and safely maintained.

Pre-established priorities: Priorities for the task reassignments required by irregular operations also need to be pre-established and supported by company policy and training. Embodying the notion of

"A" tasks and "B" tasks where tasks are unambiguously prioritized, the switch from normal to irregular operations should be associated with a comparable task priority list as well. As an example: PF will fly the aircraft and handle ATC communication while PNF handles secondary communication and becomes active systems controller. As systems controller, PNF will either initiate a procedural worklist (irregular procedure checklist) or begin a situation assessment of the system. The PNF must be able to invoke rules for interpreting the system of alerts and cautions during critical phases of flight. Whether "full mode" or "split mode" switching is used will create a need for different rules.

Recommendations in Irregular Operations

- Minimum equipment list design
  - accommodate the implications of degraded automated capabilities
- Task reassignment
  - establish priorities
  - rules for assignment
  - determine level of automation operation

SUMMARY

In summary, there are four major areas in which crew coordination is affected by increased fight deck automation. To take full advantage of the benefits of automation, the following elements are essential in the coping strategy:

1. There must be an increased emphasis on crew concepts in both training and operations areas.

2. There must be better pilot-to-pilot communication during ALL phases of flight.

3. There must be a complete understanding of tasks and responsibility for task accomplishment in the more highly automated environment.

4. Aircrews must know when and how to transfer from automated to semi-automatic to manual operations as the situation dictates. This implies both systems and interface knowledge as well as alternate courses of action available when normal operations are interrupted or no longer available.

Flight Deck Automation: Promises and Realities
Final Report of the Working Group on
UNDERSTANDING AUTOMATED SYSTEMS

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INTRODUCTION

Since the introduction of the autopilot into aircraft more than a half century ago, automation has taken over many of the tasks which were once the exclusive domain of the human pilot. When machines control or perform tasks and pilots are relegated to a monitoring or supervisory role, questions arise as to the extent pilots need to understand these systems. Understanding a system means not only being aware of what it is (or is not) doing, but also knowing the reason for a system's action and anticipating what the system is going to do next. In general, the need to understand a system is closely related to the need for intervention by the pilot if the system fails to operate as designed or, in the opinion of the pilot, is operating in a manner which compromises safety.

This report is intended only as a summary of the discussions conducted by this working group. A comprehensive review of known or of potential operating problems with automated systems is beyond the scope of this report. Problems which exemplify more fundamental issues in training, design, or operating procedures are provided for illustrative purposes only. Likewise, the solutions to these problems which have already been implemented or are recommended should not be construed as exhaustive of possible alternatives.

CURRENT OPERATIONAL PROBLEMS

For current operational aircraft, problems involving the pilot's understanding of automation can occur in two areas: flight path management and aircraft subsystems management. To date, automation of subsystems management does not appear to present a problem for aircrews. However, the current state of affairs may change as aircraft age increases and subsystem failures occur more frequently.

The more immediate problems are associated with flight path management. Examples in this category are usually associated with Flight Management Systems and related areas of computer control of the aircraft flight path. Problems of standardization of mode control panels are repeatedly cited by aircrews. The problem appears particularly acute in the area of status annunciation where confusion may arise as to what is and is not under automatic control. The problem of standardization of mode control interface design has been aggravated by the mixing of aircraft fleets resulting from the large number of recent airline mergers. Lack of pilot-system interface standardization increases the cost of training and increases the potential for pilot errors in line operations.

Distinct from these problems of standardization in design are problems which arise from inadequacies in the pilot-system interface of an automated system. Errors can and do result when system status annunciation is unclear or ambiguous. For example, if a Flight Management System can engage an autopilot independently of an autothrottle, the system should make the pilot aware that the system is operating in this "split mode." Lack of pilot awareness due to preoccupation with other duties can result in changes of aircraft attitude in the absence of coordinated throttle inputs. If the pilot, for whatever reason, is not aware of the status of the system, intervention may well occur too late.

Annunciation of gradual or "soft" failures of autoland systems is another example where pilot-system interface design is particularly important. With the aircraft in close proximity to the ground and configured for landing, awareness of an autoland system's impending loss of function becomes critical as rapid and precise pilot intervention may be needed. As increasingly sophisticated automated systems are introduced in areas involving the operating limits of an aircraft, addressing the problem of soft failure annunciation will become more important.

Closely allied to the problem of status annunciation is the need for pilots to understand the design intent of an automated system. Currently, this receives little, if any, attention in the pilot training process. The design intent underlying an automated system can often help the pilot understand what such a system can and can not do during actual operations. Windshear-induced autopilot hysteresis is an example. Sudden changes in the direction and speed of the wind can result in autopilot-induced pitch control oscillations. These excursions can be quite large, and if occurring close to the ground, catastrophic. Understanding system design should cause the pilot to disconnect the autopilot immediately. However, pilots may be reluctant to do so if they attribute capabilities to the system that it does not actually possess, e.g., that it has the intelligence to adjust to unusual operational conditions. Failing to understand the capabilities and limits of automated systems are persistent problem areas in operating such systems.

COPING STRATEGIES

For current aircraft, coping strategies adopted to overcome operating problems with automated systems fall into three areas: training, operating procedures, and after-market design changes. As is typical with any design problem, training takes on a disproportionate role. Unfortunately, pilot training on automated systems has been recognized as being less than adequate in both areas of systems understanding and use of the system in line operations. Incorporation of automated system operation into existing Line Oriented Flight Training (LOFT) is occurring, although the cost of this type of training is high. Alternative strategies of systems training employing computer-based training systems are also being considered.

The second means being used to cope with automation problems is to change the procedures for using the system in line operations. For example, operating an autopilot separately from the autothrottle is now prohibited by some carriers as is the operation of autopilots in windshear and severe turbulence. Most, if not all, of these changes have resulted from an operational incident or accident. This trial and error coping method is inherently undesirable as it may incur enormous costs in lives and property. Operating limits of systems should be clearly defined prior to line operation as should the potential of these systems for design-induced human error.

Finally, after-market design changes can have limited use in ameliorating operating problems with automated systems. Improving status annunciation symbology and operating interfaces have some value in this regard. Improving Control Display Unit design to provide easier re-programming of the FMC is one such example as is enhancing the speed with which the FMC will accept pilot inputs. However, such changes are often difficult and expensive. In some cases, annunciation displays and associated interfaces that could enhance pilot awareness of an automated system's status cannot be accommodated in the cockpit without a major re-configuration.

ON THE TECHNOLOGICAL HORIZON

Obviously, the time to address design issues is during the design process. However, aircrew training to understand and operate future automated systems will always be necessary and should be factored into the cost of operating any advanced system. Fundamental design and training philosophies for automated systems need to be established for future advanced technology aircraft if operating problems with these aircraft are to be avoided. Advances in computer technology will almost certainly result in even more complex levels of automation than are currently available. The result will be increased demands on limited training resources.

Issues that are on the technological horizon are varied and far reaching in their potential impact on pilot interaction with automated systems. Examples of these include the incorporation of ground-air-ground data link systems which will make possible the automation of clearance delivery to the FMC. Automatic warnings of altitude deviations and of descents below minimum safe altitudes, automated altimeter settings, and many other services are possible. Increasingly sophisticated flight control systems are also on the horizon including gamma flight path control,* envelope protection, and relaxed static stability. Airframe subsystem management will become more sophisticated with the introduction of intelligent systems and the use of decision aiding technology to facilitate failure diagnosis. Clearly, determining the extent of pilot understanding needed to effectively control automated systems will become even more important in future aircraft than it is today.

RECOMMENDATIONS

It is evident that the knowledge required to fly automated aircraft requires more than simply knowing which button to push and when. However, it is important to emphasize that the fundamental role of the pilot has not changed (but see Addendum). This role is made explicit in FAR 91.3: "The pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft." As part of this role the pilot has in the past, and continues to, perform the function of systems monitoring and flight path management. The machinery by which an aircraft is operated does not fundamentally alter this role though it may simplify or eliminate the need to perform certain tasks. This leads to the working group's first recommendation: That a philosophy of flight deck automation be adopted which assures that the pilot plays an active role in the management of the aircraft flight path and that any information which affects that management should be provided either in the training process or as an integral part of flight deck design.

Secondly, the development of flight deck information management principles are needed to support the integration of automated systems in future aircraft. Knowing what kind of information is needed, when it should be provided and in what form it should be presented are essential to the design process. Standardization of functional requirements for automated systems interfaces, particularly in mode control panel design, is also needed as are guidelines to minimize the possibility of design-induced errors on the part of aircrews. Such standardization require-

* Editor's note: Either automatic or pilot control of aircraft inertial velocity vector.

ments will require a more active role on the part of regulatory agencies than currently exists.

Thirdly, the integration of automated aircraft into the Air Traffic Control (ATC) system and the eventual automation of that system suggest that problems of aircraft-ATC integration will increase unless a comprehensive systems analysis effort is undertaken. A key element in that effort should be the delineation of the role and responsibilities of humans (pilots and controllers) in an automated air traffic control system.

Finally, the training of aircrews of automated aircraft must emphasize the understanding of automated systems and how these systems can and cannot be used in line operations. The design intent underlying an automated system should be an important ingredient in training program development.

ADDENDUM

The definition of the pilot's role in automated systems is not without controversy. It should be understood that others have taken the position that the role has been altered by the tasks, i.e., it is a role that is more passive, less manual, etc. It may be that these differing viewpoints result from focusing attention on different levels of the pilot's task hierarchy. In any case, this issue undoubtedly deserves more extensive consideration than is possible within the scope of this report.

Flight Deck Automation: Promises and Realities
Final Report of the Working Group on
TRAINING FOR ADVANCED TECHNOLOGY AIRCRAFT

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INTRODUCTION

Airline pilot training provides the interface between transport aircraft and the pilots who operate them in day-to-day line operations. Training is obviously important and, despite the use of sophisticated simulators and other advanced training aids, it continues to be very expensive. While there is no disagreement within the aviation community regarding the importance of effective pilot training, there is considerable disagreement on the kind and amount of training that is required to enable pilots to operate new and different airplanes safely and efficiently within the aviation system.

Today, there is a consensus among training experts, both within and without the industry, that regulatory requirements (and those training practices that are based solely upon them) have not kept up with advancing cockpit technology. It is not surprising that such training is not efficient and, perhaps because of an apparent excessive preoccupation with automation, it has not always been sensitive to the wide gamut of operating needs of the pilots who routinely fly these aircraft.

There is, therefore, a very clear need to review all of the factors involved in contemporary airline pilot training. It is particularly important to review the training from a systems perspective because of the interaction of the many factors that are involved.

Airline pilot training, even without the complication of advanced cockpit technology aircraft, is a very complex subject. Its complexity is exacerbated by such factors as some very basic differences in airline operations, the widely varying training resources of airlines that range from the established trunks to newly-formed commuters, the varying needs of pilots with a wide range of established skills and experience, a broad range of aircraft and aircraft systems and an ATC system badly in need of modernization. In addition, all of these aircraft must be operated safely and efficiently in day-to-day line operations in a dynamic variable operating environment. It was not possible to fully cover all aspects of airline pilot training in the time allotted to us.

Therefore, the Working Group did not deal with those specific areas nor with a host of traditional generic training issues such as the kind and level of fidelity needed in cockpit procedures or limited part-task trainers, the role of "motion" in instructional simulators with full motion capability, the optimum amount and kind of feedback for computer-based instruction (CBI), the design of training programs based on present regulatory restrictions, adapting training programs to the varying needs of a diverse pilot population, problems in "differences" training, the effectiveness of the variety of teaching methods and teaching devices currently available, etc. Because it did not deal with these and similar items, the Working Group does not mean to imply that they are not important.

However, in order to take advantage of the current general industry consensus that reexamination of airline pilot training principles, practices, and regulatory procedures is sorely needed, the Working Group concentrated on identifying general areas it believes should be included in the current reexamination of airline pilot training. It identified seven general areas it believes should be included in such a reexamination. The seven general areas are listed below and will be discussed in the following paragraphs.

1) Review of FAR 121 Appendix E (initial) and F (recurrent) training requirements

2) Human factors training for "Decision Makers" in the industry

   - FAA
   - Manufacturers and their vendors
   - Airlines
   - Pilot associations
   - Airline trade organizations (e.g., ATA, RAA, and IATA)
   - International organizations (e.g., ICAO)
   - NTSB
   - Specialized training organizations

3) Pilot training in automation

4) The role of the manufacturer and its vendors in training

5) Standardization and simplification in automated aircraft

6) Workload management in the 2 person crew automated flight deck

7) The potential role of digital flight data recorders in training

REVIEW OF FAR 121 APPENDIX E AND APPENDIX F TRAINING REQUIREMENTS

The requirements specified in Appendix E (initial, transition, and upgrade flight training) and Appendix F (pilot proficiency checks) apply to all airlines operating under Part 121. They, in conjunction with the training requirements of FAR Part 121 Subparts N and O, effectively control air carrier pilot training in the United States for all airlines other than those commuter airlines that operate under FAR Part 135.

The Working Group believes that present regulations are not fully responsive to the technical and operational requirements of contemporary air carrier operations, and that a full review of FAR 121 training requirements is urgently needed. It fully supports the training objectives of the Administrator's Task Force on Flight Crew Performance in this area and believes this subject should continue to receive a very high priority.

In addition, the Working Group believes that the review process should be formalized to ensure that similar reviews are made periodically on a predetermined schedule or can be made in response to technological advances.

HUMAN FACTORS TRAINING FOR "DECISION MAKERS" IN THE INDUSTRY

Over the years there has been growing recognition that human factors should be considered a "core technology" in all parts of the air transport system including the air traffic control system, the design, manufacture, and operation of transport aircraft, and the regulation of these basic elements. All of these affect training requirements.

The growing recognition of the importance of human factors, like so many aspects of this dynamic industry, has been evolutionary. Not surprisingly, its growth has not proceeded at an equal pace among all elements. The consensus that "human factors" should be considered a core technology on a system basis has been only recently achieved.

The Working Group believes at least two things are required to take full advantage of the human factors potential to improve the safety and efficiency of air transport operations:

a. First, individuals responsible for decision-making at all levels affecting design, training, operations, and regulation (and this includes those with responsibility for the allocation of funds) should have training (or indoctrination) in human factors. This should be at a level that ensures awareness of the importance of human factors, and in particular, its relevance to air transport operations. The training (or indoctrination) for these decision makers should be of sufficient depth to enable them to recognize human factors needs within their area of responsibility, and to recognize the need for additional expertise in specific areas when such a need arises.

   Organizations with such responsibilities include the FAA, aircraft manufacturers and their vendors, the airlines, pilot associations, the NTSB, and specialized training organizations.

b. Second, it is equally important that members of the scientific community interested or involved in air carrier operations receive sufficient training or indoctrination in those operations to ensure that their recommendations and research are responsive to real-world needs and problems.

PILOT TRAINING FOR INCREASINGLY AUTOMATED AIRCRAFT

[Note: All of the recommendations in this section apply to both FAR Part 121 and Part 135 carriers]

Basic Airmanship Skills and Knowledge

The Working Group believes that the addition of sophisticated cockpit automation systems has not reduced the need for or the level of basic airmanship skills and knowledge which have traditionally been required of airline pilots. Therefore this discussion assumes that pilots transitioning to advanced cockpit technology aircraft already possess those skills and that knowledge. In addition, the importance of the extension and application of those fundamentals to the advanced technology aircraft should be emphasized in the early phases of both ground school and simulator training. General aircraft familiarization should always precede detailed instruction in automatic features.

Monitoring of Automatic Systems

Effective monitoring of the operation of automatic systems is an increasingly important responsibility of the flight crew. The development of methods to increase monitoring effectiveness should be given a high priority. Cockpit resource management (CRM) courses that emphasize the importance of monitoring and the role and increased responsibility of the pilot-not-flying (PNF) are needed. In addition, the importance of monitoring activities should get greater emphasis in both training and checking activities.

It is particularly important that transition training includes not only the operation of the automatic systems and their limitations, but also their "design intent." It is not reasonable to expect pilots to effectively monitor the operation of automatic systems without providing them a clear understanding of how the system they are monitoring is planning to accomplish its specific task.

LOFT

One of the major advances in the training of airline pilots during the past decade has been the development of line-oriented flight training (LOFT). However, because LOFT is still a relatively new concept there have been wide variations in both its use and in the quality of the training provided.

Despite these difficulties, the Working Group believes there is a need for greater use of LOFT in initial training in order to better prepare pilots for line operations. There was a weaker consensus that in recurrent training, the primary use of the simulator should be in a LOFT environment. It is important to recognize that recurrent LOFT can be conducted in the more elementary visual simulators as well as in Phase I, II, and III simulators.

Cockpit Resource Management (CRM)

There is a growing consensus within the aviation community concerning a pressing need to improve cockpit management and cockpit crew coordination. Although a variety of CRM training programs have been developed, the possible need for CRM programs modified or tailored for the pilots of advanced cockpit technology aircraft has been essentially ignored.

The Potential Use of Home Computers in Training

The sensitive and intelligent use of home computers to fulfill training requirements and for voluntary self-instruction should be explored. While there are obvious potentials for misuse, there is also a considerable potential for fulfilling the needs and desires of all of the parties involved—air carriers, pilots, and the FAA. Implementation, however, can be a particular challenge for air carriers and the representatives of their pilots.

The Role of the Manufacturer and its Vendors in Training

Determination of the general training requirements needed to enable pilots to operate new equipment safely and efficiently should be considered an integral part of the design process. Determination of training requirements at the design stage of any changes or updates developed subsequent to the original design are equally important. These requirements need not be, and probably should not be specific, e.g., at the SBO (specific behavioral objective) level, but should clearly indicate what the designer of the system believes the pilot should know in order to operate that system safely and efficiently.

After the initial design and the inevitable compromises and tradeoffs inherent in the manufacturing process have been completed, it is a logical extension of this philosophy to have the manufacturers of transport aircraft and their vendors play a larger role in two important training areas. The first training area is in the development of the specific training objectives required to satisfactorily operate their products. The second training area is in the development of the training aids, techniques, materials, etc. needed to achieve those training objectives.

STANDARDIZATION AND SIMPLIFICATION IN 2PC AUTOMATED AIRCRAFT

There is a great need for more emphasis on standardization and continued emphasis on the simplification of all aspects of the design and operation of 2PC (two-person crew) automated aircraft. It should be given a very high priority by both the manufacturers and the purchasers of their aircraft. This problem has been exacerbated by the increasing number of aircraft leasing organizations, airline mergers, consolidations, etc. that are a part of the contemporary airline scene. Different names for the same item, different procedures to operate essentially the same system, and different symbology to display identical information can create very real problems for the crews who have to cope with them. Unfortunately, this frequently happens under less than optimum conditions.

This by no means should be construed as a restriction on the development of improvements in transport aircraft. However, it seems very clear that a great deal of the lack of desirable standardization in current aircraft has little to do with improvements in the aircraft, their systems, or their cockpit symbology.

For the same reasons, this emphasis on standardization and simplification should be extended to flight operations and equipment manuals, operating procedures, and checklists. This is primarily a responsibility of the airlines and, to a somewhat lesser extent, the regulatory authorities. It should be given a high priority. However, it should be noted that, particularly in the case of operating and equipment manuals, this emphasis on simplification does not imply that these documents should not contain the often detailed information and data required to fulfill their basic functions.

WORKLOAD MANAGEMENT IN THE 2PC AUTOMATED FLIGHT DECK

Air carriers are urged to take a new and creative view of flight crew workload in automated 2PC aircraft. 2PC operational procedures and checklists should be carefully reexamined with particular attention to the workload required to perform them. Many carriers have a strong history of 3PC operations and there is considerable evidence that their operation of 2PC automated aircraft does not reflect advances that have been made in cockpit technology and in our understanding of flight crew behavior. The problem has been exacerbated by the large number of flight crew members who have transitioned to these aircraft from a 3PC airplane.

Properly developed LOFT scenarios can be used to illustrate heavy workload conditions and identify problem areas. For example, a prominent problem area in current operations, and one that present training (and/or procedures) has not dealt with effectively in many cases, is whether or not to continue to use automated navigation systems when ATC clearance changes are received during the final stages of an approach. In these cases, the important decision is often simply whether or not to continue to use automation and reprogram or to simply turn the automation off. If flight crew workload is further increased by inappropriate policies or procedures, the problem can be clearly identified during the LOFT exercise.

Considerable flight crew workload can be created by the requirement to perform non-operational, but important, tasks at particularly inopportune times. For example, calls for passenger connections, meal requirements, wheel chairs, and other passenger service items can be more than just a nuisance to the flight crew. This is by no means a new problem, but is becoming more critical because of the proliferation of high-density operations. In many cases these flight crew tasks may be either further automated (as in the case of many ACARS functions), eliminated or reassigned.

THE POTENTIAL ROLE OF DIGITAL FLIGHT DATA RECORDERS IN TRAINING

This is an admittedly controversial item. The Working Group believes consideration should be given to the system-wide use of digital flight recorders to identify areas needing training emphasis. It can also be used to identify those that are not creating problems. This is not a new idea. It has been used successfully by several foreign carriers with the sanction and complete cooperation of their pilot unions. The key provisions have been a clear recognition by all parties that the sole purpose of the program has been to improve the safety of their operations and that the rigid restriction on the use of this data has been honored.

The sensitivity of the recommendation creates a formidable challenge for all of the parties involved. The challenge is to develop procedures that permit taking advantage of state-of-the-art technology for their mutual benefit. The ability of data from digital flight recorders to improve safety and, in some cases, to justify a reduction in training requirements and training costs requires a cooperative intelligent utilization of that data. If this can be achieved, problem areas can be identified early, and safety can be improved. The reduction of training requirements and therefore training costs is an additional potential benefit.

SUMMARY

Historically, airline pilot training has developed in a relatively piecemeal and unexamined manner. While a great many changes in the industry have been essentially evolutionary, the cumulative magnitude of these changes has created a pressing need to reexamine current operating procedures and training requirements in light of automation's demands and in the opportunities it presents to the aviation community.

The recognition of human factors as a core technology has been a major breakthrough. Another has been recognition of the need to reexamine our training needs from a total system perspective. The challenge, and it is a challenge to both the operational and scientific community, is to take full advantage of our new-found knowledge.

Flight Deck Automation: Promises and Realities
Final Report of the Working Group on
ERROR MANAGEMENT

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INTRODUCTION

The objective of this working group was to identify the influences, both positive and negative, of cockpit automation on the occurrence and detection of error on the flight deck.

A key goal in the design of aircraft cockpits, aircraft operating procedures and crew training is the reduction of incidents and accidents attributed to human error. Some have claimed that automation can eliminate human error by removing the pilot from the control loop. Others have claimed that while some types of error may be reduced the automatic equipment itself introduces opportunities for new types of human error. The new equipment may eliminate small errors but introduce the possibility of large errors. These new error forms seem to be particularly difficult to anticipate during the design phase.

The group discussed: the changes in cockpit systems that have affected the type and frequency of crew errors; examples of types of human error that have been reduced; and examples of new types of human error.

The key output of this working group was a list of "high" priority and "medium" priority automation issues and recommendations that relate to errors and error detection in current and future advanced technology cockpits.

HIGH PRIORITY ISSUES

Industry Wide Error Data Base

The design of aircraft cockpits is an evolutionary process. Each new cockpit design is an attempt to improve on the past designs. If the cockpit designers know that pilots systematically make specific errors in operating a piece of equipment, they can often design the new equipment so that an error is either impossible or much less likely. To make this process work the designers must know about the types of error that are occurring. Currently there is a large body of operational experience which is not known to the flight deck designers. An industry wide data base should be established to record errors and incidents that can be used for design of future systems, upgrades to current avionics software or changes in current training courses and procedures. The IATA has an incident data base that might be adapted to this use.

Training for Highly Automated Aircraft

Training should be organized so that the pilot can always answer the following questions about an automatic system: What is it doing? Why is it doing it? and What will it do next? The pilot needs to know the system well enough to be able to predict what it will do in different contexts. Training should contain information on how the designers intended the system to operate (e.g. FMS and autoflight). This information is often lost in the long chain between designer and operator.

Error Detection & Correction: Self and Automatic

Humans make and usually detect errors routinely. The same mental processes that allow humans to cope with novel problems can also lead to error. Bill Rouse has argued that errors are not inherently bad but their consequences may be. He proposes the development of "error-tolerant" systems that detect errors and take steps to prevent the consequences of the error from occurring. Research should be done on self and automatic detection of random and unanticipated errors. For self detection, displays should be developed that make the consequences of errors immediately apparent. For example, electronic map displays graphically show the consequences of horizontal flight plan entry errors. Vertical profile displays should be developed to make apparent vertical flight planning errors. Other concepts such as "energy circles" could also help the crew detect gross flight planning errors. For automatic detection, systems should be developed that can track pilot activity, infer pilot intent and inform the crew of potential errors before their consequences are realized. Systems that perform a reasonableness check on flight plan modifications by checking route length and magnitude of course changes are simple examples. Another example would be a system that checked the aircraft's planned altitude against a data base of world terrain elevations.

Situation/Systems/Configuration Awareness

Comprehensive knowledge of current status is necessary to make appropriate error-free decisions. In autoflight control systems, the pilot should know how close the system is to its performance limits. Trend information should trigger annunciations of potential loss of control authority problems. For example the message, "You are using up your control authority," might have been helpful to the crew of the China Air flight that lost control of a 747 on a flight to San Francisco after a single engine failed. Similarly after a subsystem failure, the pilot should be able to call up displays showing the consequences of the failure in terms of remaining subsystem functionality and any new operational limitations.

Decision Support and Information Management

Systems should provide information appropriate for the current flight situation. This could include suppression of non critical information during critical phases of flight. The system should also be capable of answering WHAT, IF and WHEN questions to support the pilot in exploring options and deciding on a course of action.

MEDIUM PRIORITY ISSUES

Cockpit Resource Management (CRM) and Crew Coordination in Advanced Technology Aircraft

Good cockpit resource management (CRM) is an important element in the detection of crew errors. The CRM concept was developed with older lower technology and may need to be updated for the new two-crew advanced technology cockpits.

Standardization

Standardization of equipment would reduce errors due to transitioning between cockpits but it may have a negative impact on progress. We do not want to standardize on an error-prone and difficult to use design. Unfortunately, standardization is most important on complex systems like the FMS that most need to be improved. In addition, renewed emphasis should be placed on standardization of fundamentals which affect human performance.

The Minimum Equipment List

Operational decisions as to what equipment is on the minimum equipment list (MEL) should consider the human role. It was felt that the designer's concept of how the aircraft should be operated was sometimes compromised by decisions which allow the aircraft to operate when certain equipment is not functioning. Flying with MEL items should not result in operation below a minimum level of capability. This minimum level should include the normal displays. It was felt that much valuable training time could be saved if training for operations in very rare backup configurations was not required.

Error Management: Inform vs. Protect

Should an automatic system inform the crew that they are about to exceed the performance envelope of the aircraft or should it unilaterally prevent the aircraft from exceeding its performance envelope? This issue is closely related to the larger issue of the proper role of automation in the cockpit. It is a very important issue but there may not be any empirical way to address the problem. It is also not an "all or none" issue. An "inform" cocoon could be inside of the "protect" cocoon. A "protect" cocoon could be turned off in certain situations at the pilot's discretion.

On-Line Help

Help functions should be provided on the control display unit (CDU) for nonroutine operations to reduce the need for in-flight consultation of the manual. This will help insure the optimum use of equipment and help prevent errors.

Workload Management (Boredom and High Workload)

Resolution of the role of automation in the cockpit should enhance workload management. In addition, during long flight legs, consideration should be given to on line training of complex systems such as the flight management system (FMS). Other possibilities are interactive electronic flight manuals.

Error-Focused Design Methods

Theories of human error and design guidelines developed by cognitive scientists should be applied to the design of new cockpit systems. For example, Professor Donald Norman's new book, "The Psychology of Everyday Things," describes a theory of human action and error and offers numerous guidelines on how to design systems that are easy to use and less error-prone.

Human Factored Certification Methods

The certification process should include explicit human factors criteria. Numerous methods have been developed in the field of human-computer interaction for evaluating the adequacy of an interface design. These methods should be adapted to provide more objective evaluation methods and guidelines for human factors certification criteria.

SUMMARY

In addition to these specific automation issues and recommendations, the group members felt that defining the proper role for the automation in a human-centered aviation system was of fundamental importance in the prevention and detection of crew errors.

Flight Deck Automation: Promises and Realities
Final Report of the Working Group on DESIGN AND CERTIFICATION

Chair: Richard Gabriel, Douglas Aircraft
Vice Chair: William Reynard, NASA-Ames Research Center
Members: Donald Armstrong, FAA-Aircraft Certification
Norman Geddes, Search Technology
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INTRODUCTION

The issues of design and certification of transport category aircraft are both complex and interrelated. Certification regulations, to some extent, do effect design decisions. But the current certification criteria, relating primarily to workload and automation factors, are not specifically identified. The working group on design philosophies and certification was charged with identifying the major factors underlying the effective use of automation technology, its introduction into an operational environment and directions for the future in design and certification.

A major question which must first be addressed is, "Why should automation be introduced onto the flight deck?" Although many answers could be given to this question, among the most important are:

1) It allows the flight system (crew + aircraft) to attain a broader operational capability.

2) Economic efficiencies can be more easily obtained. The most notable example is in fuel management.

3) System consistency is improved. The introduction of automation allows for the reduction of operational variability.

4) Automation has clearly enhanced safety.

With these positive aspects of automation identified, it is now possible to proceed with a discussion of how the design and certification of automated systems might be improved and what are the major issues surrounding such an improvement.

DESIGN

The issues surrounding the design of automation for the flight deck are complex and interrelated. The discussion of this topic is organized into the following six subjects: the design of the interface, the pilot's role, evaluation criteria, current performance, impact on the NAS as a whole, and redesign/retrofit issues.

Design of the Interface to the Automated System

Among the most central of the issues is the design of the interface to the automation since the crew must communicate with the automation through this interface. This communication will be required regardless of the ultimate role or responsibility assigned to the crew. "Unfriendly" interface designs seem to be among the most common complaints about automatic systems. This is particularly true in the design of those automatic systems which are affected by the ATC environment. Unfriendly interfaces are a bigger problem when there is a requirement to modify the data/instructions to the automation under the pressure of time and/or short notice.

Interface designs must also assure appropriate situation awareness. Careful attention must be given to the effects of consistent presentation of status information and prioritization of cautions and warnings. Preservation, where possible, of tactile cues to maintain awareness is also important.

For computer controlled systems, consistency in data entry, information retrieval, and procedural aspects are very important. Page seeking should be minimized and on-line "help" should be available as necessary. Systems such as the PMS, FMS, INS, OMEGA, ACARS, TCAS, and Mode S were among the systems felt to require the most careful interface construction.

Automation, particularly that associated with the CRT or glass cockpit, may also be a distraction in the cockpit. The extent, or even whether this is a serious issue, is not known. The issue of concern is the time and/or attention dedicated to adjusting or changing the automatics as opposed to flying the aircraft.

Role of the Crew and Automation

A critical question both in this working group and throughout the conference are the roles of the automation and the crew. The preponderance of opinion was that the automation should take a greater role in the basic stability and control of the aircraft, particularly for aircraft which have relaxed and/or unstable flight modes (e.g. tilt rotor concepts). Higher level functions, however, such as flight planning/replanning, system status management and decision making, should not be completely relegated to the automation.

This view is primarily based on the fact that the fundamental pilot functions have not changed and are not expected to change regardless of future improvements to aircraft and/or the NAS system. In particular, the basic flight crew functions are to:

aviate, navigate, communicate, and operate.

The goal of automation should be to aid the crew as they participate in the task and manage the aircraft as a system.

With respect to operating philosophies, there is a difference between automated and non-automated aircraft. The responsibility of the pilot is the same in both types of aircraft but the actual activities required to accomplish these tasks are very different depending on the level of automation. In recognition of this fact, several carriers have elected to divide their fleet so that pilots do not fly both automated and more manual aircraft in the same time frame.

One central issue regarding the role of the pilot and automation is that of designs which try to provide error protection. Envelope protection has been cited as an example of this form of error proofing. On the positive side of this issue, this trend is consistent with the historical trend toward increasing automated intervention, particularly in the guidance and control area. On the negative side, however, such error proofing is not as reliable as hoped. These systems have failed and will continue to fail. Although the design goals hoped to achieve failure rates of less than 10 to the minus 9, the actual operational experience has been (and will continue to be) much lower than this number, because designers are also human. They are also subject to error and, in particular, are not able to anticipate every possible operational situation, particularly in the complex aviation environment.

It is, therefore, very important to provide a manual override for automated systems and to provide the pilot with the mechanisms for a greater role in decision making. In particular, it is important to distinguish between those automated systems which completely perform the task and those which aid the pilot so that the crew is a participant in the system.

Another question is whether a high level of automation would violate FAR 91. Automation should not take away the Pilot-In-Command's authority and responsibility. In short, the design should not isolate the human from the ability to intervene and manage the aircraft at all times.

The role of the crew is summarized in Figure 1. The central circle, situation dominance, indicates that the flight crew must maintain "legal" awareness and control/dominance over the aircraft status. The crew must have the information and ability to exercise operational judgement, contingency management, systems management, and flight planning and replanning. In addition, all of these functions must have an appropriate "manual" capability. The role of the automation should be to support the crew particularly in guidance and control, navigation, and system monitoring.

Evaluation Criteria for Automated Systems

Several characteristics were suggested which could be used to define an appropriate implementation of automation versus a poor implementation. As discussed above, it is very important that the implementation be user friendly. Ease of training is a natural corollary to such an implementation, since a good, self explanatory design can reduce the need for extensive training. In addition, functional adaptability is important. More definitive guidelines or criteria need to be established so that designers can evaluate systems as early in the design phase as possible.

Performance of Current Automated Systems

The general discussions regarding current automated systems indicated that functional systems such as the FMC (flight management computer) are the ones with the principal issues. Other automated systems such as those for fuel and pressurization work well. Again, the central issue seems to be that of designing interfaces which can facilitate and support the active role of the crew.

More specific information could also be used in this area. To what degree, if any, are the operational crews uncomfortable with the kind or degree of automation?

IMPACT OF AUTOMATED FLIGHT DECKS ON OTHER PARTS OF THE NAS

The National Air System (NAS) is composed of many interacting elements. A new technology implementation in one part will necessarily impact the other elements. The introduction of new automated technology onto the flight deck has, however, been incremental. This is, of course, the usual method for introducing new technology. It can, however, cause problems to occur particularly where the older technology must interface with the new.

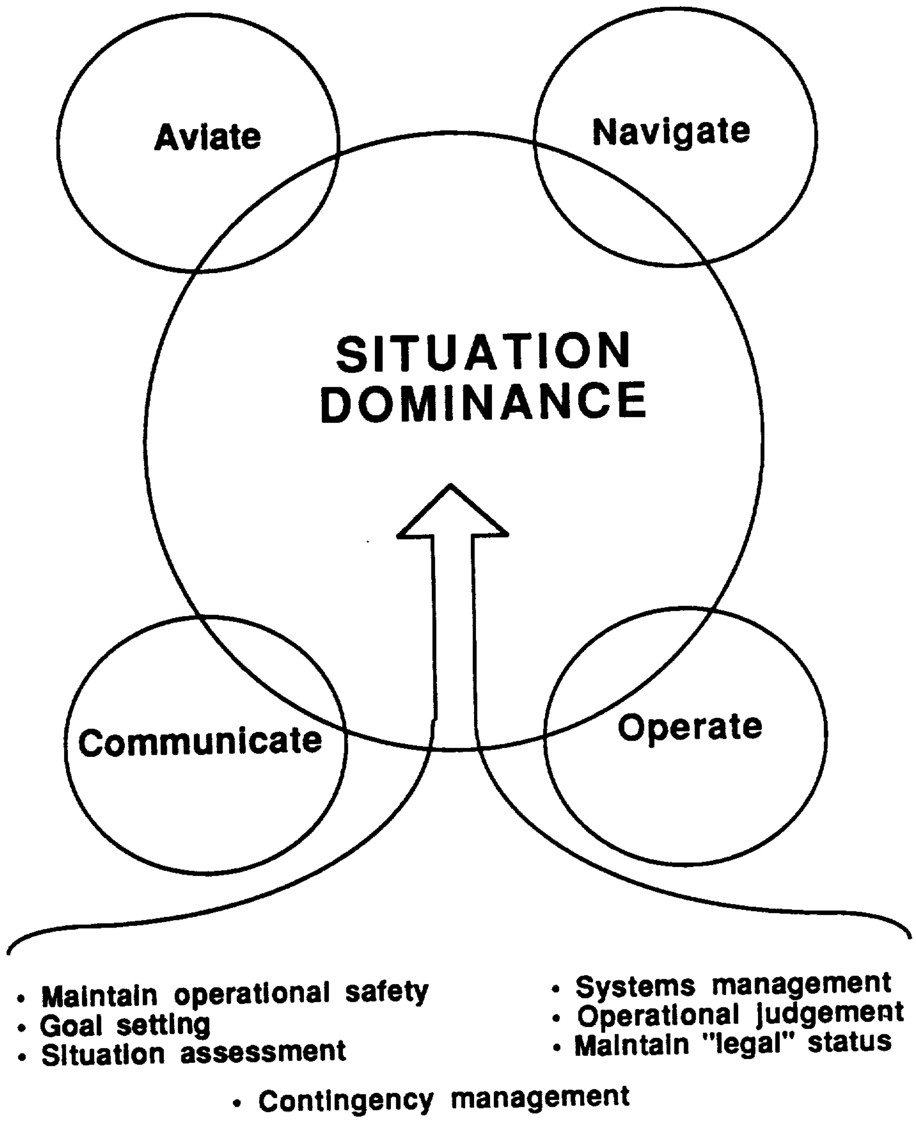

Figure 1

For example, the ATC system is currently in the process of being updated, but automated flight decks must currently interface with the existing, less-automated ATC technology. Although there is clearly an impact from the incremental introduction of automation, the magnitude is not understood. Future implementations would do well to study the impact of a new implementation on the total system, before it is introduced so that potential system-wide anomalies could be evaluated before the operational phase begins.

Redesign/Retrofit Issues

The current organizational process for designing and approving systems does not adequately address the issues associated with redesign and retrofit. In the introduction of a new technology, lessons are frequently learned or apparent only during the operational phase. This may necessitate a redesign and/or a retrofit into the existing fleet. However, the cost of redesign, certification, and retrofit often make the actual implementation impractical and operations may continue for years using the existing system supplemented only by aircrew training. The panel report on operational experiences cited some examples where this type of operational "crutch" had not been effective.

Summary of Design Directions for the Future

The major issues associated with the design of future automated aircraft are summarized below.

1) ROLE OF THE FLIGHT CREW: SITUATION DOMINANCE

  - Pilot's Role Must not be Compromised
  - Tasks can be Appropriately Delegated to Automation

2) ROLE OF AUTOMATION: AIDING THE FLIGHT CREW

  - Optimize Resource Efficiency & Economy
    - permit crew to do more in a complex environment
    - achieve better perspective of "big picture"
  - Reduce Operational Variability
  - Enhance Safe Operations

3) DESIGN PHILOSOPHY: HUMAN-CENTERED AUTOMATION

  - Achieve Objectives Cited Above
  - User Friendly
  - Adaptable to Function/Option
  - Support Crew in Functions which do not Compromise Crew's Role of Situation Dominance

4) INTERACTION OBJECTIVE: CREW INVOLVEMENT & PROFICIENCY

- Use a Systems Approach to Assure Flight Crew Manual & Cognitive Proficiency
- Designs with Crew as Backup should Permit Ease of Task Recognition & Performance without Confusion, Hesitancy, or Lack of Skill
- Eliminate Growing Tendency to Peripheralize Crew Involvement and Function

5) CRITICAL DESIGN NEED: DETERMINATION OF BENE–FITS AND LIMITATIONS OF STANDARDIZATION

CERTIFICATION ISSUES

The certification issues are broadly grouped into 3 categories: Certification policy, validation of automated systems/software, and human factors criteria.

Certification Policy Issues

The current FAA philosophy regarding certification generally does not attempt to influence the introduction of new technology in any way. The position is largely one of allowing industry to move as necessary to build the best possible aircraft. The FAA role is simply one of evaluating the "safety" of the resulting aircraft. As we have seen, however, the introduction of new technology itself can contribute to operational safety issues. This is particularly true due to the rapid introduction of advanced, computer based technology onto the flight deck.

The philosophical issues surrounding the question of constraining the introduction of new technology are complex. No specific recommendations regarding this issue were made by the group, but it is a factor which should receive further discussion.

Another philosophical issue involves certificating to standards versus certificating to guidelines. Most other aircraft systems such as structures, are primarily hardware based and specific numerical standards can be developed. Automation, however, is a combination of many disciplines including computer hardware, software and human factors. The complex interaction of the components does not always lend itself to specific standards. In addition, the technology is changing so rapidly that it would be difficult to develop exacting standards which could be effective over the next decade. In view of these factors, the use of guidelines for automation as opposed to standards should be discussed.

A last policy issue, but one of primary importance, is the way that the certification process considers (or does not consider) the trade-off between understandability and training. Since the design of the interface to an automated system was an important issue in the previous section, the philosophy of certificating to the "understandability" of an interface is most important. Currently such trade-offs between the need for training and the complexity of the design are not usually apparent. Perhaps they should be.

Validation of Automated Systems/Software

Software validation is not usually an easy process and yet it is very important to the proper functioning of most automated systems. The certification process must insure that the software will function as expected under all conditions. Yet, is it possible for the certification process to adequately make this assurance? How can this best be accomplished?

Human Factors Evaluation Criteria

The hardware components of an aircraft receive substantial testing before they are certificated. This testing typically involves stressing the structure to the failure point in a "shake and bake' manner. The automated systems aspects, particularly those associated with human factors, do not receive such thorough testing. This is partially true because such tests and procedures are only now becoming available. An issue of concern is the extent to which more and better human factors testing of systems is required prior to certification.

Summary of Future Directions for Certification

The major issues associated with the future directions for certification of automated aircraft are summarized below.

1) RE-EVALUATION/DESIGN REVIEW REQUIREMENT

   - No Certification Standards can be Appropriate over the Entire Life of an Aircraft
   - After a Reasonable Service Time, Operational Shortcomings Should be Addressed

2) FULL/PART MISSION SIMULATION TO TEST DESIGN

   - To Help Prevent Costly Redesign
   - To Permit Certification Staff to Observe and Prepare for the Flight Test

3) REVISE AND STRENGTHEN CERTIFICATION PROCESS

- Crew Interaction
- Automation Interface
- Human Performance

4) ESTABLISH INSTITUTIONALIZED COMPREHENSIVE FEED-BACK SYSTEM

- To Identify Opportunities for Subsequent Design Review
- To Anticipate Next Generation of Aircraft

5) ESTABLISH MULTI-DISCIPLINARY CERTIFICATION DESIGN REVIEW

- At Beginning of New Aircraft Development to Learn, Review, Critique, etc.

6) ESTABLISH CRITERIA FOR ASSESSMENT OF HUMAN PERFORMANCE DESIGN AND ENGINEERING

- Provide Design & Engineering Guidelines
- Assist Certification & Review Processes

7) FLIGHT DECK AUTHORITY FOR FAA CERTIFICATION AND FLIGHT TEST PERSONNEL

8) ESTABLISH BETTER COORDINATION AND COMMUNICATION WITHIN FAA RE: AIRCRAFT DESIGN/CERTIFICATION

SUMMARY

AND

CONCLUSIONS

SUMMARY and CONCLUSIONS

Susan D. Norman
Chair

INTRODUCTION

The material presented at this workshop provided a particularly comprehensive and broad overview of automation in the air transport system today. It is, therefore, not easy to select the most important points from the workshop and prepare the conclusions. This section will focus on the major, global themes.

SUMMARY

A very condensed summary of the major ideas and concepts presented in the panels and papers is given here in order to form a basis for the conclusions. A brief section on common themes of the Working Groups is also included.

Design Issues

Although specific data regarding accident/incident rates for automated versus non-automated aircraft are not readily available, it is clear that automated aircraft have a good, operational record. For example, one carrier stated that they have been flying the Boeing 767, one of the first aircraft to employ substantial automation, since 1982 and they have never had an accident or incident resulting in damage to the aircraft.

One manufacturer cited principles for effective system design in the following priority: simplicity, redundancy, automation. The goal is to use automation when necessary, but automation should not be a goal in itself. Design issues are first solved with simplicity, then redundancy, and finally automation.

Certification Issues

A fundamental issue with respect to certification is the lack of comprehensive human factors requirements in the current rules. Although the reasons for this situation are complex, the result is that design engineers must necessarily make critical design decisions long before the flight tests occur. In the absence of rules which incorporate human factors criteria, the question is whether or not the concerns of the FAA test pilots and the line pilots he represents are adequately considered.

With respect to certifying automated aircraft in today's environment, several factors were cited as important. These are:

- *Crew alerting systems*
- *Manual operation of an automated aircraft*
- *Crew over-confidence in automation*
- *Identifying circumstances where automatic protection is a clear benefit (i. e. angle of attack protection, etc.)*

Operational Considerations

Although automation has been a clear benefit, some factors were cited which have been involved in incidents with automation. These include:

- *Inadequate operational knowledge on the part of the crew*
- *Inadequate cockpit discipline and allocation of responsibilities between the pilot-not-flying and the pilot-flying*
- *Inadequate cockpit resource management*
- *Operation in split mode (e. g., operation of autopilot without autothrottle)*
- *Poor switch discipline*

Lessons Learned from Non-Aviation Automation Experiences

Numerous examples have been cited throughout this document of lessons learned from our current understanding of designing and operating automated systems. Dr. Woods summarized these as follows:

- *Shifts in automation have changed the human role in unforeseen ways.*
- *Critical human role is to adapt to unanticipated situations.*
- *Automation changes required human skills, but does not eliminate them.*
- *Automation introduces new error forms and types of system breakdown.*

In designing for human centered automation, the machine/automated system should always provide support for the human. It should display information on what it is doing, what it will do next and why. Provision of support for the human role in error detection and recovery is also most important with computerized systems.

Field Studies in Aviation

Dr. Wiener reported his interim findings of a study of two air carriers and flight crew evaluation of the B-757.

- *High enthusiasm for the B-757*
- *Training is good, overall, but there is too much emphasis on automation rather than the basics.*
- *ATC limits the use of some features (e. g., VNAV)*
- *Workload may be increased or decreased.*

Captain Peter Heldt, chief technical pilot for Lufthansa, reported the results of a pilot questionnaire on the A310-200. Overall, the pilots liked the automation, but "keeping the pilot in the loop" was cited as mandatory for automated systems.

Advanced Automation System (AAS) for ATC

The schedule for implementation of the AAS calls for the first site delivery at the Seattle Center in April, 1992, with the equipment expected to be operational at all sites by June, 1995. The system will provide:

- *New automatic separation-assurance techniques*
- *More direct, conflict-free routing*
- *Better traffic metering techniques*
- *Increased controller productivity*
- *Capacity to handle projected air traffic growth*
- *Tie together all FAA primary enroute and terminal ATC facilities*
- *Provide greater system reliability (max. down time - about 2.5 min/yr)*

Common Themes in the Working Group Reports

Several themes were repeated in the working group reports. Some of these are:

- Design of the pilot/controller interface is crucial and it must provide support such as status annunciation and display of an appropriate level of situational awareness for their intended roles.

- The air-ground interface design is critical and yet there is an apparent lack of coordination/research in this area.

- Definitive human factors criteria need to be developed.

- Since aircraft automated systems must support the role of the pilot, it is most important to understand this role and to develop some level of consistency for this role among the various components of the aviation industry from airframe manufacturers to operators.

CONCLUSIONS

Automation is a Clear Benefit

Although most of the text of this report relates to issues regarding improvements to our design, operational use of and training for automation, an important fact to remember is that automation has substantially improved the operational safety and efficiency of our air transport system. As with the introduction of any new technology, there are components and factors which cannot be clearly and completely understood without the severe and challenging test of day to day operations in a real environment.

Aviation is perhaps one of the most demanding, real-time environments for use of any new technology due to the vast number of daily operations and the complexity of the ATC interaction, weather, etc. The safety record for automated aircraft, however, is very good. The relatively smooth introduction of cockpit automation into the existing system must be taken as a tribute to the technical ability of the aviation community.

Even though the safety record for automation appears to be good compared to the previous generation of aircraft, the potential for improvement in our ability to design, certificate, use and train for automation was apparent at the workshop. In particular, the aviation environment is not one where flights always proceed as planned. Weather problems, ATC clearance revisions, emergencies and equipment malfunctions, and even combinations of these events, occur more frequently than we would like.

Yet automation is a technology which works best in predetermined situations such as those which can be planned and programmed ahead, either at the time of design or on the ground before take-off. Automated systems, because they are really machines, are designed or programmed primarily to handle the "normal" situations which account for most of the flying hours. However, the technology is not yet well enough developed to provide quick and easy flexibility when the external situation changes.

This phenomenon has been called "brittleness" and it is a characteristic which has been associated with automation (particularly expert systems). It is not wrong in itself; it is merely a limitation of the technology which must be considered in the design, certification, training and procedural use of these systems. Non-aviation industries have experienced the same phenomenon and much can be learned from their experiences (refer to the Woods paper in this document).

As a result of factors such as brittleness, irregular operations in an automated environment can become the most troublesome. Irregular operations, discussed in more detail in the working group report on crew performance, are flights in which normal operations have been interrupted or are no longer possible. In these situations, the pilot's operational understanding of the system, and how it will perform under the varying conditions, becomes crucial. The design must support this pilot role by providing appropriate display information. In addition under these circumstances, the human role is often to maintain the boundaries of the automated system, perhaps by methods such as inserting an erroneous wind vector, so that it can function effectively.

Understanding (Figure 1) thus becomes a key concept. The ability of the flight crew to understand the automatics must be supported by all phases of the aviation process from design through training and operations.

UNDERSTANDING is a Key Concept

- **Of the Way it Works**
- **Of the System Intent**
- **Of Control Laws**
- **Of Normal Versus Irregular Operations**
- **Of the Implications of System Status**

Figure 1

A point must be made regarding the actual systems which have been automated. It was generally agreed that the automation of aircraft subsystems has been much less troublesome than other systems such as those which support navigation. For example, autofuel and autothrottle systems have functioned very well and their operation appears to be easily understood in the cockpit. These systems, however, do not depend on external information sources such as pilot data entry and ground transmitting stations. As such, they do not always have the inherent interface complexity of other automated systems, such as those used for navigation.

Because the factors which affect the performance of an automated system can be complex and may not always be immediately apparent, the crew communication in the cockpit and with ATC about the operation of the aircraft must compensate for this situation. In addition, actions on the part of the automatics may sometimes be transparent to the crew. In older technology aircraft, these actions are performed and checked by a crew member. In summary, the use of automatics necessitates closer crew communication as well as a closer interaction in all phases from design to operations (Figure 2).

CLOSER INTERACTIONS

A Close Interaction is Required in All Elements of:

- **Design**
- **Training**
- **Operations**
- **ATC**

Examples:

- **Between the Automatics and the Flight Crew**
- **Between Crewmembers on the Flight Deck**
- **Between Flight Deck Design and Operational Procedures**
- **At the System Design Level (System Level Perspective)**
- **Between the Flight Deck Crew and ATC**

Figure 2

Comments from the Participants

The following comments from verbal remarks and anonymous evaluation forms may help to provide a basis for understanding the essence of this document. Participants were asked the most important new idea or issue learned at the conference:

"The basic human factors associated with automation are generic and are not being adequately addressed by either ATC or cockpit automation designers."

"Man must not be replaced by but rather learn to make effective/efficient use of automation in the aircraft environment."

"The problems generated by introducing automation in the cockpit are very similar to the problems encountered in automating the control tower..."

"Automation is working very well in many applications and users want more, not less; but there are problems that need work."

"The automation problem is very broad and it is very important to attack it systematically."

A valuable part of the conference was the exchange of ideas on ..."how others are coping (training and operational tips), what design changes and enhancements are in store and the concepts of automatic, semi-automatic, and manual operation when control is necessary in a time constrained or irregular operation."

Direction for the future is also an important issue and several pertinent comments were made regarding it.

"The role of the pilot should not change. Automation has to be added carefully. There needs to be early design guidance to accomplish good automation."

"We must find ways to introduce the equipment more effectively. In my training experience, a number of pilots were very reluctant when first introduced to the new equipment."

One of the most critical areas to emerge as a need for the future is the "development of improved interaction between the air and ground sides of the National Air System.... I am concerned that the cockpit is expanding beyond the ATC capability. This may cause the airborne side to be incompatible with the ground operations and pilots may not use new systems."

"The industry is trying to run with its brakes on. Information dissemination, particularly to the higher levels of manufacturing and operational management, is essential.

The Role of the Pilot

One important issue to emerge from the conference concerns whether or not the role of the pilot has changed as a result of automation. Several controversial ideas were discussed and I have elected to quote from several letters written to me as chair after the close of the conference. Drs. Rolf Braune of Boeing and Earl Wiener of the University of Miami most articulately presented the relevant issues in this debate and their views are cited here.

The definition of terms becomes crucial in this discussion and "goal," "role" and "functional level" are all important aspects. Regarding the goal of the pilot/ flight crew, Dr. Wiener writes that the goal of the pilot is:

> *"....to fly the aircraft from A to B with maximum safety, minimum cost, and maximum passenger comfort. This strategic goal is unchanged, but in order to achieve this goal, tasks and subtasks are carried out, and these, of course, have been altered by automation and other cockpit equipment..."*

As stated, this goal (to fly the aircraft from A to B .....) for the flight crew is relatively uncontroversial; however, the issues of role and the impact on the specific tasks which the flight crew must now perform in an automated environment are more difficult to assess.

Regarding the role of the pilot, Dr. Rolf Braune pointed out that:

> *"...the role of the pilot has not changed and probably will not change until Federal Air Regulation (FAR) 91.3 is changed. This regulation states that the pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft. This is a clear definition of a role. As part of this role, the pilot always performed the functions of monitoring and managing. What the automation technologies are attempting to do is to provide the pilot with the tools which will simplify necessary tasks or eliminate unnecessary tasks."*

Dr. Wiener, however, concludes that the role of the pilot has changed. He writes:

> *"Role refers to a more global construct than a list of tasks. It refers to the function of the crew member in realizing his strategic goal. This function, or role, has been altered by the tasks. The pilot's role is more passive, less manual, more cognitive, etc. To fail to recognize this is a serious impediment to our understanding and eventual resolution of the 'automation problem'.*
>
> *The role of the pilot is changing and our job is to understand the implications of this change."*

Although the above basic statements of the issues are equally valid, both points of view draw very different conclusions regarding the apparent change in the role of the pilot. Clearly, FAR 91.3 gives the pilot in command ultimate authority and in this sense, the pilot's role has not changed. But the methods which pilots use to perform their duties have been dramatically altered in the automated environment.

Dr. Braune further clarifies the important difference here when he writes,

> *"The apparent disagreement over whether the role of the pilot has changed or not may arise because we are looking at different functional levels of the pilot's task hierarchy. A functional hierarchy of the commercial pilot's task environment should be developed. This would help to identify:*
>
> - *those functions which may have changed,*
> - *effects of the change,*
> - *ways to counter those with negative effects,*
> - *level of these functions.*
>
> *In addition, there is a limited amount of objective data to help focus on the real issues. We may be confronted with over-generalizations which do not help understand the real causes of the issues we have discussed, particularly in light of the highly favorable accident statistics for advanced technology aircraft."*

In summary, the consensus at the conference was that the role of the pilot should not change. The flight deck crew must be actively involved in the operation of the aircraft and the substance of FAR 91.3 should remain in effect. However, as the tools and methods used to fly aircraft change, the choices which a pilot can realistically exercise may also change. It is in this sense that a fundamental change in the pilot's ability to accomplish the intended role may occur.

Unfortunately, as Dr. Braune has correctly pointed out, there is a paucity of data regarding the actual, operational task responsibilities of the flight crew. Due to this lack of data, only opinions can be given. As chair, it is my opinion that the intended role of the pilot has not changed, but that the actual ability of the flight crew to exercise much of the assigned role/authority has indeed been changed by many factors including the ATC environment as well as the implementation of current flight deck automation.

Dr. Braune indicated the need to understand the pilot's task hierarchy more clearly and Dr. Wiener suggests that it is our job to understand the magnitude, as well as the implications, of these changes. Both of these needs are important topics for future research, particularly if we are to understand clearly how to use automation technology more effectively.

DIRECTIONS FOR THE FUTURE

Although much has been accomplished regarding automation of the flight deck, there is still much to do. The workshop provided a valuable opportunity to exchange experiences regarding operations and training for automated aircraft. Continuation of such opportunities needs to be provided by the relevant organizations and government agencies.

The need for quantifiable data regarding the implementation and interface designs for automated systems is also very apparent. Full mission simulations which compare alternate displays, etc. and test the performance of the entire system (ATC + flight crew + aircraft) would be very helpful.

Improvement in the human factors aspects of the certification process is needed.

Additional research is needed to better understand how to support the human role in an automated environment. This involves interface design, training and operational procedures.

Improving our understanding of the air-ground interface is crucial for the future. This development is necessary if coordination of the planning and implementation of advanced automation for both the flight deck and the air traffic controller are to proceed in a integrated manner. Automation provides the potential for one part of an automated system to impact another, sometimes without direct human intervention. As a result, it is important to examine the implementation of automation as an overall system so that the design implications can be made visible before the operational phase commences.

APPENDICES

APPENDIX A

AIRCRAFT AUTOMATION PHILOSOPHY: A SOURCE DOCUMENT

This report was prepared to provide
an initial basis for discussion for the participants in
the NASA/Industry/FAA workshop,
"Flight Deck Automation: Promises and Realities,"
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This report was prepared based
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Automation: "automatic operation or control of a process, equipment, or a system" (American Heritage Dictionary, 1976)

Automatic: "acting or operating in a manner essentially independent of external control; self-regulating"—but also, "lacking volition, intention, or conscious planning" (American Heritage Dictionary, 1976)

AIRCRAFT AUTOMATION PHILOSOPHY: A SOURCE DOCUMENT

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AIRCRAFT AUTOMATION PHILOSOPHY: A SOURCE DOCUMENT

1.0 Introduction

Assessing the impact of automation on civil transport aviation is difficult and complex. Although many major benefits have been realized from the introduction of new technology onto the flight deck, there is an underlying concern about its implications and long term effects.

One recent report which reflects broad aviation concerns states, "The recent and rapid introduction of advanced computer-based technology onto the flight deck of transport category aircraft has been associated with a dramatic change in both aircraft operations and the role and expertise expected of the flight crew. Although no specific accident statistics are available, there have been a number of serious incidents, which necessitate development and testing of a critical, scientifically based philosophy of automation" (Norman, et al., 1988 p. 1).

A discussion of the framework for a "Philosophy of Automation" and the need for its development form the basis for this paper. An automation philosophy can provide guidelines and constraints for answering design questions and a methodology to evaluate both individual design decision and the overall utility of the automation.

Beginning with a historical context for issues related to automation, this paper explores the consequences of current automation and describes a direction for the future which could lead toward a Human-Centered Philosophy of Automation.

2. The Evolution of Automation in Civil Transport Aircraft*

This section describes the historical evolution of automation technology, in the hope of discerning trends in the respective roles and functions of automation and of the humans who will operate these aircraft.

* This section is reprinted from an unpublished manuscript entitled, "Toward Human Centered Automation", with the permission of the author, Dr. Charles E. Billings.

2.1 The Beginnings

In the earliest days of manned flight, automation technology was needed to stabilize the aircraft attitude by directly controlling the aerodynamic surfaces. Gyroscopic devices were well suited to this task.

> In 1891, Sir Hiram Maxim secured a British patent for a gyroscopic stabilizer. Five years later, it was installed and tested on a steam-powered flying machine (Pallett, 1983). Orville Wright was more successful with an automatic stabilizer that activated the wing-warping and elevator mechanisms associated with control of roll and pitch. The device was patented in 1913 and later won a Collier Trophy for its inventor (Prendergast, 1980).
>
> The following year, Lawrence Sperry received a French safety award after the successful flight demonstration, in Paris, of a two-axis system (Heinmuller, 1944). In 1918, H. J. Taplin patented a system that relied on aerodynamic pressures. His device was successfully flown in 1926 in the United States, but is not known to have been used thereafter (Taplin, 1969).

2.2 Early Autopilots

Gyroscopic devices have dominated aircraft inner loop control (maintenance of attitude for all spatial axes) since that time.

> A Sperry "automatic pilot" was installed in the Winnie Mae in 1932 and was used extensively by Wiley Post in his successful circumnavigation of the globe in 1933. A later model Sperry gyro pilot was installed in the Lockheed Electra which Howard Hughes used for his global flight in 1939.

By the beginning of World War II, autopilots were installed in a variety of long-range aircraft. With vacuum-driven gyroscopes (which often provided cockpit attitude and heading reference as well), these devices were the cornerstone of automatic flight throughout the war and for several years thereafter. They alleviated fatigue and freed pilots from the burden of constant manual aircraft control.

Following the war, autopilot technology advanced rapidly. Vacuum-driven gyros were replaced by more effective electrical systems and processing of autopilot error signals was taken over by electronic amplification.

The transition of radio navigation from low frequency ranges and non-directional beacons to very high frequency omnirange (VOR) transmitters simplified the navigation process, insulated it from electrical storm interference, and provided more precise directional data. The output of these radio aids, when coupled to autopilots, provided the ability to track radials with respect to a VOR station. The output of the VHF instrument landing system (ILS) was also used to provide precise tracking of localizer beams, while the corresponding glide slope transmitters were coupled to pitch axis control for vertical guidance.

Precise data regarding magnetic heading, altitude and position with respect to external references, when integrated into the autopilot system, enabled considerable outer loop, as well as inner loop, control. When commercial jet aircraft were introduced in the late 1950s, this state of the art prevailed. Solid-state electronics had not been applied to aircraft. Autopilots were still large, bulky and temperamental, but when they worked they provided the pilot with:

— two or three axis inner loop control of aircraft heading
— the ability to capture and maintain a magnetic heading
— the ability to capture and maintain a VOR or ILS track
— altitude hold and the ability to track a glide slope
— altitude select and capture ability, in some cases.

2.3 The Second Generation

Turbojet transport aircraft (the de Havilland Comet in 1952 and the Boeing 707 in 1958) provided substantial increases in speed and altitude capability, but required more precise inner loop control, particularly at high altitudes. Newer, more precise flight instruments were required by the pilots of these aircraft.

> Pallett notes that "Flight instrument evolution has followed a pattern of divergent display complexity with advancing technology followed by consolidation of the displays as human capabilities of data interpretation were exceeded." (1983)

Flight directors were introduced to provide command information for both the pilots and the automatic devices. Integrated with altitude indicators, they directed pilots to climb, descend and turn to new headings or radials; thus they enhanced inner loop control of the less stable swept-wing aircraft configuration, especially during low visibility and high precision maneuvers. Pilots came to rely increasingly on these flight directors, although substantial concerns were expressed at the time regarding "losing sight of the raw data" from which the flight director derived its information.

The tendency of swept-wing aircraft to yaw away from banked turns (Dutch roll) prompted the introduction of automatic devices which counteracted this tendency (yaw dampers). Fast jet aircraft were similarly equipped with pitch trim compensators which counteracted the tendency to pitch down at high Mach numbers. These devices could be turned off, but in practice they were used without crew intervention.

During the 1960s, advances in solid state electronics made newer, more competent autopilot/flight director systems possible. These systems incorporated complex control laws including flare logic for automatic landings and provided a stepwise increase in automatic flight capability. As a further improvement, the automatic throttle logic integrated control of power and flight path. These systems were introduced in the DC-10, L-1011, and other aircraft.

The initial impact of these new types of automated systems led to flight crew reports of difficulty in learning to operate the more complex system aspects. Training was modified to emphasize system operation. Pilot certification began to require a full demonstration of the pilot's ability to use the new systems to full advantage under a wide variety of circumstances where previous requirements had emphasized the ability to operate without such aids.

In 1975, after a series of "controlled flight into terrain" accidents, Congress mandated the installation of ground proximity warning systems (GPWS) in transport aircraft. These devices used radar altimetry to evaluate height above ground and its rate of change; they provided light and voice warnings/commands to the cockpit crew when predetermined parameters were violated. Crew responses to the GPWS warnings were mandated by aircraft operators, but no attempt was made to implement these automatically (i.e., without crew intervention). Such systems did, however, represent a further extension of the "automated command" philosophy first embodied in the flight director systems, because they annunciated a command for the pilot to maneuver the aircraft. This was a significant extension from the previous use of automatic devices which only maintained stable aerodynamic or navigational control. Today, wind shear advisory and collision avoidance systems are further extending this philosophy.

In the late 1970s, the introduction of area navigation systems (first Doppler and then inertial) and their integration with the autopilot, added another dimension to the level of automation complexity in some cockpits. By the beginning of the 1980s, airline cockpits in the operational fleet ranged from almost fully manual jets which had been manufactured during the 1960s to newer, highly automated aircraft. This mix of variously configured automation types has in itself caused incompatibilities.

2.4 The Third Generation

The next major steps in cockpit automation were the sweeping changes associated with the introduction of both the more flexible electronic CRT displays, the "glass cockpit," and the automated system management devices. This automation was motivated in part by economics as well as the desire to reduce the workload to a level which permitted the aircraft to be safely operated with only two cockpit crew members.

Aircraft such as the DC 9-80 (now the MD-80) incorporated simplified, but sophisticated, aircraft management and electronic flight control systems while retaining the electromechanical instruments. Systems control was now affected through computers such as the flight management computer and alphanumeric control display units (CDUs) used for data entry.

About this same time, Boeing introduced the 757/767 aircraft which used color cathode ray tubes (CRTs) for primary flight information and engine and aircraft system data. The format of the primary displays, however, retained the conventional, electro-mechanical presentation. One exception was a new and highly capable map display format which presented an effective alternative to the horizontal situation indicators that had been used since the early 1960s.

These systems, along with the slightly later introduction and retrofit of new flight and performance management systems, completed a major revolution in the cockpit. Yet the implications of this new technology were only beginning to be understood. While manual flying was still possible, it was not encouraged or even practical under some circumstances. Pilots were evaluated largely on their ability to use fully the vastly more capable integrated flight path and aircraft management systems. Operationally, the new systems enabled vertical as well as horizontal automated navigation and guidance. Under normal conditions, thrust management as well had become almost completely automatic. In the final evaluation, pilot and crew workload for routine situations was considerably reduced. Other implications were, however, yet to be explored.

The new systems provided pilots with the capability to increase flight path precision, and equally important, to do so with maximum fuel economy. They enabled fully automatic routine flight virtually from takeoff to rollout, regardless of weather while reducing inflight workload.

Unfortunately, it also became evident that the air traffic management system was not sufficiently adaptive to permit full use of the capabilities of the newer aircraft flight management systems.

Changes in ATC instructions required cumbersome reprogramming of flight paths through the CDUs, a task requiring considerable attention inside the cockpit perhaps during the descent or approach phase when attention outside the cockpit was most crucial. Such changes actually increased crew workload substantially and diverted them from managing and monitoring their aircraft's progress and environment. It has been said, by both human factors researchers and operational experts, that the new devices tended to increase the workload when it was highest (climbs, descents and approaches) while decreasing it when it was already boringly low (cruise and high altitude flight).

2.5 The Next Generation

The next generation of aircraft about to enter service (747-400, MD-11, etc.) have continued to introduce new forms of automation which attempt to alleviate some of the issues previously cited. However, this automation has also brought with it new forms of potential error. Some examples are discussed here to illustrate important trends.

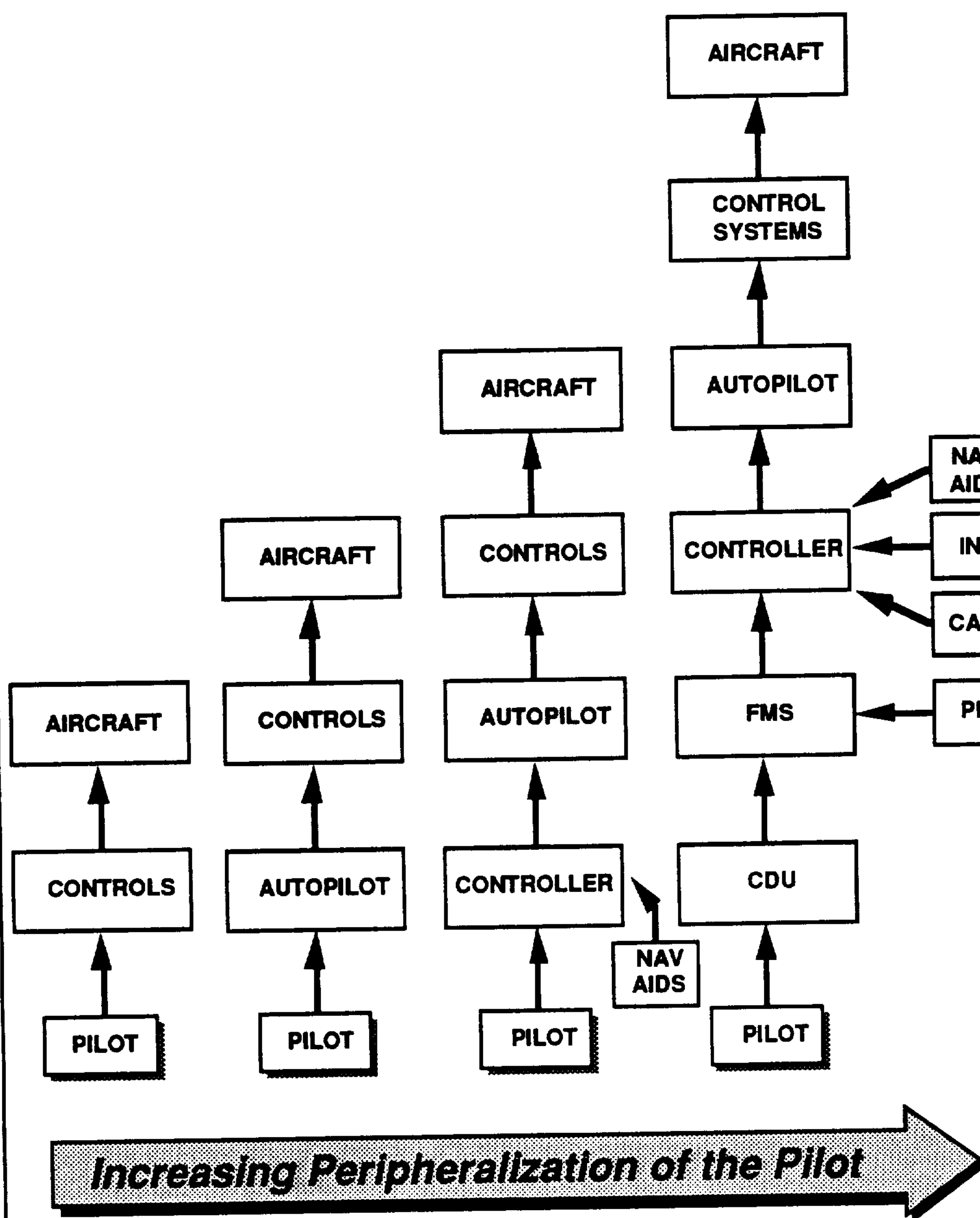
Concern about increased workload during off-nominal operations and the consequent diversion of crew attention from outside to inside the cockpit (especially at low altitude) have given rise to questions about the complexity of current CDUs. The newest aircraft now entering the production cycle incorporate attempts to simplify CDU operation by making available more comprehensive navigational data bases and by the addition of software to make reprogramming simpler. Despite these attempts, elimination of the CDU keyboard data entry has been seriously discussed.

Another technological advance about to enter service is the introduction of advanced control systems ("fly-by-wire") incorporating logic to prevent the aircraft from exceeding its safe operating envelope. Automatic limitations to angle of attack, bank angle as a function of air speed and configuration, and other control laws will insure that a pilot cannot exceed predetermined parameters established by the designers. These limitations apply regardless of the real time control inputs provided to the vehicle.

Aircraft subsystem management will also be drastically simplified to reduce workload for the smaller flight crews. Microprocessor technology has been used to automate navigational tasks as well as management of electrical, fuel, hydraulic and pneumatic systems in normal operations.

Each of these technological advances, included for a variety of reasons, has not only enabled new forms of errors, but also has had the effect of making the flight crew more peripheral to the actual operation of the aircraft (Figure 1). Whether this was intended or not is not within the purview of this paper, and is probably irrelevant. Nevertheless, the pilots who formerly exercised direct authority over all aspects of aircraft control and management, now have become responsible primarily for the management and direction of extremely complex hardware and software interfaces through which (and only through which) they may direct the operation of their vehicle.

Figure 1: Evolution of Transport Aircraft Automation



2.6 The Historical Implications: A Summary

Three major conclusions are apparent from the discussion of the history of the introduction of flight deck automation.

- The implementation of the technology has been *incremental* in nature (a component level approach was implemented as opposed to a systems level design strategy). This is common with a *technology-centered* philosophy.

The incremental development of independent, component level systems began with the gyroscopic stabilizer technology for aircraft attitude control. Flight control including fuel management became feasible and soon automated navigational control was enabled by the development and installation of ground based systems. Microprocessor and CRT technology signalled the advent of glass cockpits and automatic systems which directly commanded the pilot to maneuver the aircraft (i.e. GPWS).

- The technology has resulted in an increasing *peripheralization* of the pilot. The flight crew has been gradually removed from direct control of the aircraft to control of systems which in turn control the aircraft.

- Third, *new types of errors* have been introduced such as data entry errors and software engineering errors.

Before proceeding with aviation examples, it is important to note that these same issues have been associated with the introduction of automation in other industries and a brief discussion of the implications is instructive.

3.0 Theoretical Effects of Introducing Automation: Examples From Non-Aviation Industries

The effects of advanced technology have been widely studied in other industries and a wide body of literature regarding automation's theoretical basis and practical application has been collected. Potential solutions to problems with automation in the aviation domain may be placed in perspective based on a review of the broader experience with these technologies.

A basic challenge to the implementation of any new automation capability is to predict accurately the effects of the introduced changes on other system elements. New automation has a large range of possible effects and ramifications that go well beyond the specific task addressed by the new technology. The problem is how to achieve the potential benefits from the new technology while finding and correcting deficiencies in its utilization. Careful examination of the history of automation reveals that shifts in automation have system-level effects which may create new difficulties because the entire human-machine system has been changed in unforeseen ways (e.g., Noble, 1984; Hirschhorn, 1984; Adler, 1986).

3.1 Implications of Technology Centered Development

One assumption often made is that automation will not only reduce the number of workers but also reduce or even eliminate worker skill requirements. However, actual studies indicate that this is not always the case. Automation changes the human role and this, in turn, changes the required skills. These skills are frequently more demanding. For example, more diagnostic and fault-finding tasks occur (Miller & Bereiter, 1986; Bereiter & Miller, 1986).

Examples of unintended and unforeseen negative consequences that have followed purely technology-driven design and implementation of new automation capabilities include:

> A failure occurred during the introduction of a computer based power plant control room alarm system because the fault management information associated with the older annunciator alarm systems was simply no longer available (Pope, 1978; Kragt & Boten, 1983).
>
> Shifts from paper based procedures to computerized procedures have collapsed due to unforeseen disorientation problems by the human operator who exhibited different information needs with the new environment (Elm & Woods, 1985).

These examples illustrate that increasing levels of automation create the need for new kinds of feedback regarding the system status, its processes, and its control functions. Implications for the automation designer are substantial and will be discussed in a later section.

3.2 Peripheralization

Adler (1986) describes the process of "peripheralization" that accompanies increased levels of automation where the human's role is shifted away from direct contact with the process and becomes one of system manager, system maintainer, and/or machine prosthesis (provide eyes and hands for the system). Human peripheralization can produce the boredom/panic syndrome:

> Boredom—Situations which are within the range of competence (performance envelope) of the automation and there is little for the operator to do;
>
> Panic—Situations which approach or exceed the limits of the automation and the operator is suddenly thrown into a highly active, crucial role.

Problems have been noted in domain environments where there are extremely negative consequences to relatively rare events (e.g, in nuclear power plant settings).

3.3 Introduction of New Error Forms

The human's role, by default, is to make up for shortfalls in the automated system's ability to cope with the level of variety demanded by the operational environment (Roth, Bennett, & Woods, 1987). But, in contrast to this, the usual design principle is to attempt to anticipate all situations with the implication that designs which do not anticipate everything are bad. However, in any complex environment, including the National Airspace System, it is clearly impossible to anticipate all situations. Instead, designs should be valued for being robust in the face of violations of the design assumptions.

A new form of error can also result from the tendency of automation to increase (or explode) the number of alerting signals that an operator must monitor. This has several implications:

- Designing a supervisory control role involves the design of how the attention of the human operator should be distributed in different contexts and states.

- Designs of the human interface to automated systems should facilitate proper distribution of attention and not degrade performance or lead to a loss of situational awareness.

- There is a need to know how to design environments to support effective human monitoring.

Shifts in the level of automation can effect the type, consequences and frequency of error occurrence. Multiple, interacting factors can produce special situations. Breakdowns can occur due to ambiguous instructions, special conditions or contexts, or erroneous assumptions about the expected operation. Frequently the only way to control automatics is by controlling the input. The pilot or operator may need to work around the automatics or may enter erroneous input with possible negative consequences and/or unusual system responses.

Novel errors may be introduced when a change in one system element impacts other elements in unexpected ways. This may occur because automation usually increases the degree of coupling within the entire system. System coupling refers to the interdependence of subsystem elements. Error forms associated with highly coupled systems will increase, particularly when failures produced by several small, seemingly unrelated factors occur at the wrong time. For example, a momentary power failure or surge can result in unintentionally reinitializing the system, leading to a misperception of the current system status.

4.0 Effects of Automation Technology on Aviation

Automation has both delivered on old promises and introduced new problems. Safety of flight has clearly been improved and the ability to fly in all weather and manner of flight conditions has been an improvement to the safety, cost effectiveness and utility of aviation commerce.

Cockpit crew size has been reduced by one-third, without the imposition of unacceptable levels of workload on the remaining two crew members; the economic payoff of this change has been considerable. Area or point-to-point navigation, now commonplace, has shortened flight times and decreased fuel consumption without detrimental effects on the air traffic management system. The availability of automatic landing guidance has improved flight reliability, particularly in regional areas prone to severe weather. Flight crews, in general, give high marks to the automated systems in the newest aircraft in service.

As is always the case with the introduction of new technology, automation has had unanticipated effects as well. However, specifics of these effects are not well understood, primarily because there is a paucity of quantifiable data. But, some of the major issues are articulated in the National Plan to Enhance Aviation Safety Through Human Factors. Potential issues arising around the new, automated aircraft include:

- Substantially increased head down time.
- Difficulty in recovering from an automation failure.
- Reluctance of flight crews to take over from a malfunctioning automated system.
- Degradation of pilot skills.
- Introduction of unanticipated failure modes.
- Difficulty in detecting system errors.
- Incompatibility between advanced automated aircraft, existing ATC capability and the rest of the fleet. (ATA, 1988)

This has necessitated a reevaluation of the implications of this technology particularly with respect to the current operation and future design of transport category flight deck automation.

A complete account of the effects of advances in aviation automation technology is beyond the scope of this paper. However, a variety of problems, often only apparent after the new technology has been introduced and is being operated by real operators in real situations, have been documented in civil aviation.

4.1 Problems with Technology Centered Approaches

The impact of the technology centered approach is difficult to quantify but is readily apparent in examining occurrences of accidents/incidents with the newer technology aircraft. Systems level effects pervade most of these examples and this category is therefore not specifically discussed.

Examples related to peripheralization of the pilot are:

1. Loss of Situation Awareness: Loss of situation awareness occurs when the pilot develops, and fails to detect, an erroneous perception of the state of the vehicle and its relationship to the world. As an example, a number of authors have suggested that the pilot of flight KAL 007 may have:

a) mis-set his flight management computer,
b) failed to detect this error,
c) remained unaware that this error would result in eventual positioning of the aircraft in terminally hostile airspace.

2. *Loss of System Awareness*: Loss of system awareness occurs when operators of complex systems are fundamentally unaware of automated system capabilities and limitations or develop erroneous ideas of how the system performs in particular situations. For example, the flight crew of the China Air 747 which entered (and recovered from) a serious stall at about 41,000 feet over the Pacific Ocean several years ago was apparently unaware that:

a) the autopilot was progressively increasing angle of attack in a futile attempt to maintain constant altitude when the aircraft is not capable of maintaining altitude on only 3 engines at 41000 feet (because of failure of an outboard engine to spool up following engine idle conditions, also produced by an automatic system).

b) the automatic yaw damping system was incrementally increasing aileron control power to compensate for asymmetric yaw conditions (or unaware, functionally, that the automation would eventually reach limits in the ability to perform such compensation).

3. *Poor Interface Design*: Although in some instances it is difficult practically to separate the interface from the automation, numerous problems have been attributed to poor interface design.

> For example, reprogramming the flight management system to accommodate a change in assigned runway during the approach phase often represents such high "head down" workload levels that pilots are unable to rely on the automated system to guide this phase of flight. The automated systems under these circumstances can be turned off and a manual approach is flown.

Thus, even though the autopilot fundamentally has the capability to adapt to a change in clearance, the actual interface with the system is so complex and time consuming that its usefulness is limited when it could be most effective. Good interface design is regrettably still an art whose successful practice is limited by the experience and ability of the designer.

4. *Reversion to Manual Control*: Pilots of advanced technology aircraft understandably fear the loss of basic flight skills and many manually fly their aircraft in order to maintain this skill (Wiener, 1988; Curry, 1985). While it is difficult to find documented accidents/incidents where skill erosion has been cited as a contributing factor, it could be argued that the reluctance of flight crews to take over from automatic systems when there are good indications that something is wrong results in part from skill erosion.

5. *Automation Induced Crew Coordination Changes*: Foushee (1988) has described anecdotal evidence of a particularly subtle effect of highly automated environments. Because much of previously observable human behavior has been replaced by hidden (or hard to observe) machine behavior, one can argue for the importance of increased (and improved) crew communication. However, at least one major study of crew behavior in advanced technology aircraft suggests that crew members may actually do just the opposite. More data are needed to evaluate this claim.

Those issues related to the introduction of new error forms are:

1. *Systematic Human Procedural Errors*. In a recent industry study of accident causation (Sears, 1986), it was asserted that fully 35% of civil accidents may be attributed to procedural mistakes by the flight crew. While the reasons for such lapses are complex and incompletely understood, as an approximation they can be attributed to human limitations associated with working memory, with inappropriate attention allocation, with information processing limitations under stress of various types (e.g., time, workload, etc.), and with human tendencies to make performance "slips," which have been documented most recently by Norman (1981) and Reason (1987).

2. *Systematic Decision Errors*: A group of psychologists and cognitive scientists collectively known as "Subjective Decision Theorists" has, over the past two decades, done a revealing job of cataloging systematic biases which limit the ability of humans to make optimal decisions. Woods (1988), and others have also shown that joint or cascaded machine-human decision systems often exhibit suboptimal performance, relative to what might reasonably be expected on the basis of individual competencies. In the aviation context, the Air Florida Flight

90 accident at National Airport has been asserted (Nagel, 1988) to illustrate a variety of classical human decision limitations.

5.0 Technology Centered versus Human Centered Automation

We have argued, although it is somewhat difficult to find explicit supporting data, that the introduction of automation has been technology driven. That is, most automation technology has been implemented without a clear understanding or perhaps explicit statement of the actual problem that the technology is supposed to solve. A recent industry report states that:

> "There are many problems associated with the introduction of advanced technology onto the flight deck of transport category aircraft. Many of these arise from the lack of a consistent 'philosophy of automation'. To date, the designer has largely not been constrained by human factors considerations nor guided by a global approach to the introduction of automated systems and procedures. This has resulted in designs where the crew has been forced into the system almost as an afterthought and frequently is outside the system control loops. It also results in operations in which the human is primarily a monitor of the automated systems and yet data indicate that humans are totally miscast in this role." (Norman, et al., 1988)

Such implicit automation philosophies which have guided much of advanced systems development in aviation and elsewhere, have tended toward implementations which replace human function with machine function—the *technology centered approach.* As a result, the human has not always been left with a task environment that is fully compatible with human capabilities and limitations. In this sense, the technology driven approach also has had the effect of leaving the human out of meaningful control and/or active participation in the flight operation. This *"Human-Out"* phenomenon need not necessarily be associated with technological advances, but unfortunately it is normally what happens.

A logical contrasting philosophy to that of slowly removing the human from substantive task responsibilities is to design systems such that the human is the central element in control and management of the system—a *"Human centered"* approach. Implicit in this approach is the development of designs which:

- fully utilize and enhance the unique human capabilities of pattern recognition, information integration, learning and adaptation, etc.

- protect the system from human limitations such as systematic human error tendencies, unreliable monitoring skills, decision-making biases and limitations of working memory and "processing speed".

Note that this human centered philosophy, as stated, is mute on the topic of whether the flight crews are allowed to choose to do anything they desire.

Additional operational procedures are required which, depending on the situation (system context), would state the rules and circumstances for use of specific automated capabilities.

5.1 Toward a Working Philosophy

It is not the purpose here to define a human-centered philosophy of automation. Instead we attempt to prepare the foundation for such a philosophy by describing its basic concepts and developing a conceptual framework for design. Toward this end, the realities of the aviation environment must form the basis for any philosophy which is expected to be actually implemented.

Realities:

- The civil aviation system is complex; this complexity is increasing.
- The National Airspace System (NAS) is heterogeneous; it is a highly coupled system involving a mixture of humans and machines, each with a very broad spectrum of capabilities.
- The flight environment is highly unpredictable (e.g., weather). Problems in one part of the system have effects at distant times and places (e.g., traffic delays).
- The flight crews and air traffic controllers who operate the system, possess (now and for the foreseeable future) unique perceptual and cognitive abilities which are as yet unmatched by artificial systems.
- These same human operators have performance limitations which are increasingly well known and understood in the context of predictive modelling. For example, humans need help with very fast or very slow event sequences.

5.2 A Conceptual Framework

As we have noted, a working philosophy must be able effectively to consider three important concepts: 1) a system level perspective, 2) peripheralization issues, and 3) management of new error forms.

1) *System Level Perspective: Aviation system design must reflect global systems engineering approaches and practices. It can no longer be designed and developed incrementally using a piecewise integration of independently designed components.*

The global questions which should be directed to the automation designer and operator are best summarized by the following:

a. Is there an explicit understanding of the implications of the introduction of the new, automated technology on the total system, particularly the role of the human?

b. Have the reverberations throughout the total system been anticipated?

c. Has the new human role been properly supported?

These questions revolve around the central issues of function allocation between the human and the machine. Such choices need to be decided both on the basis of overall system effects including the performance/cost improvements and with consideration for the potential of introducing new error forms. The system perspective is most crucial.

2) *Peripheralization: In order to counteract the effects of peripheralization, human-centered automation systems must be designed which:*

a. allow for human interaction and involvement with the system which is consistent with human intellectual abilities, skill level, and responsibility;

b. allow for the joint and collaborative interaction and responsibilities of flight crews, controllers, and ground personnel; and

c. enhance unique human capabilities.

The question of providing proper support for the new role of the human after the introduction of new automation is important. Automation, as previously stated, increases the peripheralization of the human. This frequently means that the human role is changed from one of direct control to one of issuing coordinating instructions. Automation designs, however, do not always allow the operator to intervene. In these cases the person has to find ways to "get around" or "trick" the system to get it to perform correctly, particularly under special circumstances. This situation may have resulted from a form of "designer overconfidence." However, it is difficult both to design an interface so that intervention is possible and to analyze all the possible circumstances which could require the operator to intervene. But these issues are crucial to the successful use of automation and they form the basis for the design principles which follow.

3) *New Error Forms: Aviation system elements should be designed so that they are effectively protected from systematic human limitations analogous to designs which have been used to protect against machine failures.*

In the system level view, the introduction of new error forms are interpreted as symptoms of deficiencies or flaws in the underlying automation design or architecture (Hollnagel and Woods, 1983). Such errors point to the areas where improvements in the architecture of the automation are needed.

This is in stark contrast to the view that the human is an independent source of, or contributor to, errors. Yet the technology-centered approach often assumes that the pilot is an independent source of errors so that such events are often remedied by increasing the level of the automation. We have seen this frequently introduces new forms of errors.

5.3 Emergent Principles for Design

1. *Decision Support*: Joint cognitive systems should be designed to avoid problems associated with human/machine decision systems. Decision support should take the form of machine supported human decision making paradigms. They could be designed so as to reduce decision biases and provide both action sequences and their consequences. An attempt should be made to create systems that are both error tolerant and error evident. Warning and alerting systems should be: intent-driven, based on strategic goals selected by the crew; predictive, able to forecast critical conditions; intelligent, able to recognize inconsistent input; and able to give explanations if necessary. System designs should allow maximum discretion of the crew in decisions to employ or not to employ cockpit devices.

2. *Interface Design*: A most critical element is the task representational aspect of interface design. Available evidence suggests that cognitive/perceptual tasks are best mediated with information systems and displays which minimize the kind and type of mental "transformations" required to translate between physical and cognitive representations. Automated systems designers should evaluate the way the pilot would perform the same function. Intuitive design allows the pilot to understand more easily the automated system and if necessary take over from it. Additionally, consideration should be given to annunciate to the pilot how well the automatics are performing their function and how close the automatics are to their own performance limits. This clear annunciation of the status of the automation is termed *transparency*. In other words, the pilot should be able, easily and quickly to understand and check machine status and parameters.

3. *Procedures Support*: Humans are poor and unreliable monitors (Wiener, 1987). They often fail to follow established procedural protocols under actual operational conditions. New technologies (intent inferencing, activity tracking, etc.) promise systems which have the capability of "intelligently" monitoring

humans. Procedural aiding systems, which have been used successfully in process control settings, offer promise for reduction of procedural errors in aviation. In system design, procedural aspects should be considered so that lower priority pilot tasks do not interfere with the satisfactory performance of higher ones. Additionally, consideration should be given to reducing the time to switch between tasks.

4. *Crew Coordination*: Foushee (1987) has pointed out the importance of effective communication practices between multiple crew members in highly automated cockpits. Formerly visible actions of human crews have in many cases been replaced by the invisible actions of imbedded machinery.

5. *Workload Management*: The strategic management of workload consists of a redistribution of tasks, reducing workload where it is high or possibly increasing it where workload is low and the flight regime is not critical. Cockpit tasks, supporting materials, and ATC procedures should be designed to minimize head-down time during critical phases of flight. If workload is properly managed, situational awareness will not suffer due either to very demanding task requirements or low task priority.

5.4 Emergent Principles for Operation

A more complete treatment of this topic is required, but this brief statement is included to indicate that principles of operation are as (or perhaps more) important than those applied for design.

Training: Initial emphasis should be on the "basic airplane" before introducing the automation. LOFT exercises should allow flight consistent with the principle of machine-supported human decision making.

Procedures and Policy: Company policy and procedures should consider the impact of additional cockpit duties on high workload activities (e.g., making company radio calls). Careful consideration should be given to operational procedures particularly for crews flying derivative type airplanes, i.e., the fleet contains both traditional and advanced technology derivative aircraft. In these instances, consideration should be given to training issues as well as the development of procedures for the advanced technology derivative.

6.0 Toward Implementation

Much work needs to be completed before the emergent principles and other factors described here can be translated into a useful working philosophy for the design and operational environment. It is possible, however, to describe some of the realities of implementation as well as the components of a philosophy which can then form the basic framework for further work.

Current Implementation Practices:

- A new cockpit is rarely designed from the top down. Most are incremental. Design limitations must be recognized and accounted for in a philosophy.
- Currently the only human factors issue in the certification process (part 25) is workload. System level effects, peripheralization issues and potential for new errors need to be considered.

Components of a Philosophy:

A philosophy of automation specifies the crucial interactive nature of the relationship between the human and the machine.

> Any design philosophy of automation should have the following characteristics:

- Explicitly describe design and operational principles.
- Predictive ability to sort out improvements versus potential hazards in design and procedures at a gross level.
- A procedure for analysis which will enable the consequences of design decisions to be described.
- A system level, not a component level, perspective.
- Assessment criteria which allocate functions between the human and machine and a process for their application.
- An analytical test to identify inconsistencies in the application of the philosophy or problems in its implementation. The test environment should be a systems level, operationally oriented test, that would describe a non-standard but frequently occurring situation such as a change in assigned runway on a close in approach. The performance of specific data entry systems and procedures could then be effectively evaluated in these well defined, benchmark situations.

A philosophy of automation is needed to provide consistency in design and operation. It should provide a view which is consistent and, therefore, supports system reliability. A philosophy provides design constraints on human/machine interaction and is needed to guarantee that the role of the human will not be unduly compromised by design or procedural expediency, cost or simply lack of awareness.

An automation philosophy provides guidelines and constraints for answering design questions, especially where experimental data are not available or not possible to obtain. It provides a methodology to evaluate both individual design decisions and the overall utility of automation technology.

A crucial element in any philosophy is the role of the human. The difficulty is one of making a conscious choice to define and implement this role and to use technology in its support. This leads us to the last and perhaps most important questions surrounding aviation automation—the role of the pilot in the future system.

7.0 The Role of the Human in Future Systems*

It is not unreasonable, given the capabilities of automated aircraft about to enter service, to ask whether in fact the human crew could not be eliminated in routine operations. Given that air traffic control were to gain a higher bandwidth means of communicating control instructions to aircraft, would it not be possible for those instructions to be translated directly into commands for flight path management? The answer to this question, given full implementation of technology currently available, is an unequivocal "yes." If the automated aircraft systems can become sufficiently reliable (and the newest systems have been designed to be very reliable indeed), there is no reason why ground-directed flight, from takeoff roll to landing rollout, cannot be fully automated.

The fact that fully automated flight except for taxi and "unusual circumstances" is possible with at most minor improvements in current technology gives rise to the concern voiced by Wiener and Curry in 1980: *"The question is no longer whether one or another function can be automated but, rather, whether it should be."*

For many reasons, including reliability and passenger acceptance, it is extremely unlikely that unmanned, fully automatic aircraft will be introduced into air transport at any time in the near future. That statement, however, begs the question of whether *manned*, fully automatic aircraft should be introduced; that is, aircraft that require perhaps some monitoring, but no human intervention during normal operations, except perhaps during taxi and ground operations.

The question posed by Wiener and Curry is very nearly academic. Almost fully automated aircraft are about to be introduced into air transport operations,

* This section is reprinted from an unpublished manuscript entitled, "Toward Human Centered Automation", with the permission of the author, Dr. Charles E. Billings.

whether they should be or not. Perhaps a more appropriate question would be "Given the level of automation now available in transport aircraft, what should be the role of the pilots?"

Automation could be designed to keep the pilot closer to the control of the vehicle, while providing an array of information management and aiding functions designed to provide the pilot with data regarding flight replanning, degraded system operation, and the operational status and limits of the airplane, its systems and the physical and operational environment. Outer loop functions, including monitoring of operator performance, could be components of such a philosophy of automation. The pilot could call on automation modules to assist in problem diagnosis, in evaluation of available alternatives, and in execution of alternative plans. The automation would serve as the pilot's assistant, providing and calculating data, watching for the unexpected, and keeping track of resources and their rate of expenditure.

Is such "human-centered automation" possible? The answer is certainly "yes." Is it likely? Unfortunately, it is exceeding unlikely unless serious thought is given to the direction of our past and current automation development, and unless a new automation philosophy is adopted prior to the design of the next generation of transport aircraft.

We do not suggest that it is a conscious aim of the designers of current transport aircraft to eliminate the flight crew from a central role in aircraft and aviation system management. The direction of the trend in automation technology, however, may well have precisely that result. If this is not to happen, we may have gone as far or farther than we should go without making explicit our philosophy of automation and examining the directions in which our automation technology development are leading us.

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APPENDIX C

INSTRUCTIONS TO WORKING GROUPS

The most important elements of the workshop on *Flight Deck Automation: Promises and Realties* are the discussions which will occur in the small working groups. Each participant has been assigned to a specific working group. These in-depth discussions are critical because they provide the basis for the final products of the workshop.

The panels and invited papers were selected to prepare a foundation for discussion by describing ideas, concepts and terminology. The application of these concepts and ideas will hopefully lead to new, more creative ways of understanding the issues associated with flight deck automation. Since the intent of the workshop is also to be of practical value, identification of current approaches or coping strategies used with the current generation of aircraft is also important.

Although the "Philosophy of Automation" is a major topic, the conference is not intended to be theoretical in nature. It is, however, important to understand and assess the existing situation before any changes, future research programs or philosophies are developed. Obviously a view toward the future is important and should be included in the discussion, but a critical, exact understanding of the current situation must form the basis for any discussions of the future.

The time allocated to these working groups by each of the participants is very valuable and it is a rare opportunity for a broad representation of the aviation community to be able to come together to discuss complex issues.

Because of the importance of these working groups, considerable time and effort has been taken in the development of their goals and objectives. Careful consideration has been given to developing workable, productive objectives. The information attached has been prepared to initiate discussion and to assist the working group chairs, the NASA vice chairs and the individual participants.

Objectives

- Identification of the issues regarding flight deck automation
- Prioritization of these issues

- Identification of coping strategies used in current operations training, and ATC interface.
- Identification of design and operational guidelines.

Expected Products of the Working Groups

1. An informal, interim verbal report for Wednesday morning, and a final verbal report for the closing session on Thursday.

2. A final written report will be prepared (format is described below).

3. A list of terms which serve to describe automation related issues (an initial draft has been prepared by Ev Palmer).

Procedures:

Each working group has an assigned chair from the industry, and a NASA vice chair who will serve multiple functions, including host, resource person, technical and scientific advisor, and recording secretary. Detailed working procedures have been left to the discretion of each chair.

Working group assignments were made by NASA on the basis of several considerations. Please note that although we have assigned one of six specific areas to each working group, we do not mean to limit the scope of any group's discussion to the assigned area. Instead, consider the assigned area to be a focus for the primary area of consideration. If you wish to make recommendations in other areas, you certainly may do so after a thorough development of the primary area.

The working group's discussions are intended to be informal. The idea is to describe the benefits and issues associated with flight deck automation and to prioritize their importance. This prioritization should (where applicable) rank the issues by their frequency of occurrence (i. e. the most common to the least common). In addition, areas with a low frequency of occurrence, but high consequence, should be identified. Other factors such as ease of change also may be considered. It is important to note that a consensus at this point is not necessary.

Please note that two NASA participants, Susan Norman and Michael Shafto, do not have working group assignments. They will circulate among all the groups throughout their discussions.

Working Group Reports

It is the responsibility of your NASA vice chair to help the chair draft the working group report which will be submitted to the general assembly. To insure a uniform format, we ask that these reports follow the format suggested below.

Each report should consist of three major sections: (1) an Introduction; (2) Recommendations; and (3) a Summary. The Introduction should describe general features of the approach taken to the assigned issue by the working group, and other materials of a general, introductory nature.

The Recommendations section is the heart of the report. This section should directly address three topics: (1) Issues Identified and Prioritization of Issues; (2) Guidelines and Current Coping Strategies; and (3) Recommendations for the Future.

Any major areas of disagreement, minority opinions, and other similar information should be placed in the summary section.

The **interim status report** is intended to be informal. It should be a short verbal report of about 10 minutes and is intended to foster discussion among the other working groups.

The **final report** should be written (viewgraph or text) but will be presented verbally on Thursday morning. Resources such as Macintosh computers are available.

We realize that the issues described here are complex and that a full description of each issue may not be possible or desirable. Our intent is to provide a basis for understanding how these issues relate to one another and not necessarily to understand any one issue completely. With this in mind, it is more important to focus on the broad, interactive aspect of automation than to fully describe specific elements

Thank you for your participation in this workshop. It is through your efforts that we can obtain a better understanding of the complex issues surrounding flight deck automation.

Flight Deck Automation: Promises and Realities Working Group CREW COORDINATION

Chair: Al Ogden
Vice Chair: Barbara Kanki

The design and implementation of increasingly automated systems on the flight deck brings raises a variety of potential human factors issues relating to individual crewmembers. In addition to these concerns, however, there are issues which may affect the crew as a whole; that is, the way in which crewmembers coordinate their activities together. The most obvious, direct effect include changes in task structure, changes in information flow and communication channels, and changes in the interpersonal aspects of traditional and standard procedures.

There are also indirect effects (i.e., effects which are less specifically tied to flying the aircraft). These include changes in the organizational structure of the crew such as shifts in authority and responsibility as well as effects related to the problems of transition from one technology to another and training.

I. Direct effects of flight deck automation on crew coordination
  A. Changes in task structure
    i. type of tasks, e.g., active vs. monitoring
    ii. distribution of workload, "who does what"
  B. Changes in information flow/communication channels
    i. face-to-face information transfer may decrease
    ii. information may be maximally available but "who knows what" no longer public knowledge
    iii. changes in ground-based support role
  C. Changes in interpersonal aspects of standard procedures

II. Indirect effects of automation on crew coordination
  A. Social/organization issues
    i. who is in authority/who holds the information
    ii. who is responsible for shared info
  B. Effects of transition
    i. must pilots be fluent in both systems for backup
    ii. what are the rules for switching (an additional interface task)
    iii. training must incorporate changes

UNDERSTANDING AUTOMATED SYSTEMS

Chair: R. Braune
Vice-Chair: A. Lee

The purpose of this working group is to provide a forum for an interdisciplinary discussion on the need for, and implications of, operator understanding of automated systems. Automated system is broadly defined as any self-operating machinery which controls or performs tasks (e.g., an FMC). Issues included in this group discussion is the extent to which operators need to know the operating principles of automated systems and the need for maintenance of operator awareness of the status of such systems. The extent to which operators require explanations of system actions and the need for operators to anticipate actions of the system will be addressed. finally, the implications of these and other related issues on operator training, a system design, and operating procedures will also be discussed.

WORKING GROUP: AIR-GROUND COMMUNICATIONS (ATC) OBJECTIVES

Chair: Jack Wisely
Vice Chair: Renate Roske-Hofstrand

Among some of the issues to be discussed in this working group are how increased cockpit automation affects the pilot's interaction with ATC. We should discuss both negative and positive effects. Possible sample issues include the following:

1. Air-Ground Matching (Mis-matching)
2. Flight Plan Changes and CDU re-programming
3. Cooperative Behavior (Responsibility and Reliance)
4. Pilot perceptions regarding new control procedures such as:
    - Flow Management
    - ATC intervention only to prevent conflicts
    - Communications Management
    - Enroute delays

If we were tasked to establish guidelines for designers of cockpit automation what would we have to say?

What should we know about the FAA's Advanced Automation System that could or should influence the design of on-board automation tools?

To stimulate our discussions, I have attached a brief article entitled "The Quest for Airspace Safety and Capacity" which reports on the UK's National Air Traffic Services' (NATS) attempt to deal with increased demands.

Flight Deck Automation: Promises and Realities

Working Group: Error Management Issues

Chair: David Nagel
Vice Chair: Everett Palmer

The objective of this working group is to identify the influences, both positive and negative, of cockpit automation on the occurrence and detection of error on the flight deck.

A key goal in the design of aircraft cockpits, aircraft operating procedures and crew training is the reduction of incidents and accidents attributed to human error. Some have claimed that automation can eliminate human error by removing the pilot from the control loop. Others have claimed that while some types of errors may be reduced the automatic equipment itself introduces opportunities for new types of human error. Like the digital watch it may eliminate small errors but introduce the possibility of large errors. These new error forms seem to be particularly difficult to anticipate at design time.

We will discuss:

- The changes in cockpit systems that have affected the type and frequency of crew errors.
- Examples of types of human error that have been reduced.
- Examples of new types of human error.
- Methods for anticipating the impact of new technology on human behavior and on the nature of human errors.

The key output of this working group will be a prioritized list of automation issues and how they relate to errors and error detection in advanced technology cockpits.

Flight Deck Automation: Promises and Realities

Working Group

Training and Operational Procedures

Chair: Frank Tullo
Vice-Chair: Harry Orlady

Operating procedures and basic training curricula are developed by the manufacturer in order to operate their aircraft safely and efficiently under all of the conditions they may be exposed to in transport operations—i.e., standard operating conditions, abnormal conditions, and emergencies. They are then, with the approval of the airline's FAA Principal Inspector (PI), frequently modified to be consistent with the general operating practices of the airline. After the procedures have been developed and approved pilots must be trained to use them.

Pilot training for all airlines is both important and very expensive. While there is no disagreement regarding its importance, there has not always been agreement on the kind and amount of training that is required to enable pilots to operate new and different airplanes safely and efficiently. As an entirely separate issue, there is also controversy regarding the effect of automation on training requirements.

The training issues are complex. They can vary between aircraft and among airlines and over time. They can be identified and categorized in many ways. The following issues and sub-issues have been discussed at considerable length in the literature—often with considerable disagreement. Here they have been divided into four entirely arbitrary categories: 1) Conceptual or Generic Issues; 2) Implementation, Company Policy, and Procedural Issues; 3) Transition Training Issues; and 4) Recurrent Training Issues. There is considerable overlap among the categories.

I. Conceptual or Generic Issues

- The "Changing Role" of the Pilot
- Effective Crew Coordination in ADVTECH Aircraft
- Monitoring and Vigilance in ADVTECH Aircraft
- Understanding System (including Software) Logic
- Low-time Pilots in ADVTECH Aircraft
- Cabin Crew/Cockpit Crew Coordination
- Ab Initio Training for ADVTECH Aircraft
- Instructor Training for ADVTECH Aircraft
- Short vs. Long-haul Operations

II. Implementation, Company Policies, and Procedures

- Utilization of Advanced Technology
- Maintenance of Manual and Cognitive Skills
- Emphasis on "Automatics" vs. Basics
- Heads-Down Time in Traffic
- Contracted Training

III. Transition Training Issues

- Adequacy of Transition Training Program
- Sensitivity to Varying Pilot Training Needs
- Sensitivity to Line Operating Needs
- Appendix E Maneuvers and Procedures
- Initial Operating Experience
- "Differences" Training with "Common Type"
- Computer-Aided Instruction for ADVTECH Aircraft
- Effectiveness of Flight Management System Trainers
- Specific Transition Training Issues
    - Transition to EFIS
    - Aircraft Systems
    - The Autopilot/Autothrottle, FMS, and MCP

IV. Recurrent Training Issues

- Adequacy of Recurrent Training Programs
- CRM (Cockpit Resource Management) for ADVTECH Aircraft
- LOFT (Line Oriented Flight Training for ADVTECH Aircraft
- Appendix F Maneuvers and Procedures

APPENDIX D

AUTOMATION TERMS AND ACRONYMS

TERMS

Note: Terms in *italics* are defined in this appendix.

actual complexity - The actual complexity of the system is generally of interest only to the designer and the maintenance personnel. It has to do with how the system actually functions.

automated aircraft or ADVTECH aircraft - Advanced technology aircraft with CRT displays and *Flight Management Systems*, such as the Boeing 757 & 767, 737-400, 747-400, MD-88, and Airbus A-310, A-320.

automatic - "acting or operating in a manner essentially independent of external control; self-regulating"—but also, "lacking volition, intention, or conscious planning" (American Heritage Dictionary, 1976).

automation - **a.** "automatic operation or control of a process, equipment, or a system" American Heritage Dictionary, 1976) **b.** any computer processing of information displayed to the pilot or of control inputs from the pilot. **c.** using a computer to accomplish a task that was or could be done by the pilot. **d.** using a computer to make decisions that were previously made by the pilot.

backgrounded tasks - Tasks that have been delegated to another agent, either machine or human. A key factor is that the person who delegates the task remains responsible for its successful accomplishment.

breakdown - An automated system is in breakdown when its current operational environment was not anticipated by the designers of the automated system and it cannot cope with the environment to achieve its goals.

breakdown of the system image - The actual behavior of the system is inconsistent with the *system image*. This could be due to problems in the design of the system or due to hardware or software failures.

brittleness - A characteristic of some forms of automation if they cannot cope with unanticipated situations. The system performs correctly only for situations that were anticipated during the systems design.

bumpless transfer of control - Smooth transfer of control between manual and automatic control modes; for example, if an autopilot is disengaged while it is holding full right rudder, the transfer to manual control is "bumpy" if the rudder correction is suddenly removed.

clumsy automation - Automatic systems equipment which are difficult to use and understand. It may perform the necessary functions but is difficult to use.

complacency - A false sense of security induced by the reliable functioning of automatic equipment. Failing to maintain situation awareness because of a reliance on automatic equipment.

coupling - A system is highly coupled when a failure of one component of the system affects the functioning of other system components. These effects occur quickly.

Error Terms

slip - An error in which the person has the correct intent but errs in executing the action.

mistake - An error in which the person forms the wrong intent. This wrong intent may be executed correctly.

error displacement - **a.** Errors made by the system designer which are not evident until the system is in operation. **b.** The consequences of an operator error is not evident at the time the error is made. The error only becomes apparent later in the flight.

error evident - The system is designed so that errors are detectable by the operator in a reasonable time period.

error propagation - Errors in one part of the system affect the functioning of another part of the system.

error tolerant - Errors are detected by the system and annunciated before their consequences degrade system performance.

fixation - **a.** A human operator makes a situation assessment and then fails to change it in the face of new evidence that is contrary to the initial situation assessment. **b.** Cognitive hysteresis.

envelope protection - Does not allow any pilot inputs which exceed the performance envelope of the aircraft. An example is "alpha floor or alpha limit." The pilot cannot increase the pitch angle to the stall angle-of-attack. This is possible on fly-by-wire control systems.

event oriented procedures - Procedures that attempt to locate the event which is causing a system malfunction.

function oriented procedures - Procedures that attempt to maintain and restore the critical safety functions of a system. They are not necessarily concerned with diagnosing the event which caused the system malfunction.

glass cockpits - Advanced technology flight decks that use CRT (cathode ray tube) (glass) displays for the primary flight displays.

mediated - **a.** Information to the pilot and controls from the pilot are processed by a computer. **b.** The user works through a computer to accomplish a task.

Model Terms

conceptual model - The users' model of how the system works. The user can form expectations about the behavior of the system in new situations based on his or her conceptual model of the system.

design model - The designers' model of how the system works. This is the system model that the designer would like the user to have. It is also how the designer hopes the system will actually operate.

system image - The image the system presents to the user. The designer should attempt to make the system capabilities and operations evident from this image. The system image includes the design of all of the visual and interface parts of the system.

user model - This is the model of the system that the user actually develops. It can be based on the system image, training materials, knowledge of task or knowledge of other similar system.

perceived complexity - The users' view of the complexity of the automatic system. This is the complexity of the "user model."

performance envelope - The boundary conditions within which a system can perform correctly. For example, aircraft performance envelopes define power and altitude limits as a function of aircraft configuration. Conceptually, automated systems also have performance envelopes, but they are often not well understood by system operators.

redundancy - More than one independent method exists for accomplishing a function or task.

reversion - The process of switching from automatic to manual control.

supervisory control - The supervisor is responsible for successful completion of the mission. Low level tasks are delegated to other machines or human agents. Generally the automatic equipment exercises the "manual" control, while the human sets goals and monitors the system as a whole.

transparency - **a.** A computer system is transparent if the user feels that he/she is operating directly on the task and not using a computer to accomplish the task. (example: many Macintosh applications.) **b.** A computer system is transparent if it is clear how it operates.

ACRONYMS

AAS	Advanced Automation System for Air Traffic Control
ACARS	Automatic Communication and Recording System
ADF	Automatic Direction Finder
AFS	Autoflight System
AP	Autopilot
APU	Auxiliary Power Unit
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
Basic "T"	Traditional spatial configuration for display of primary flight instruments.
C/W	Caution/Warning
CAT II	Category II approaches have weather minimums of a 200 ft ceiling and 2600 ft RVR.
CAT III	Category III approaches have weather minimums of RVR 700 ft and no minimum ceiling for landing. Subcategories of CAT III have even lower minimums.
CDU	Control Display Unit - the pilot's interface with the FMC
CM1	Captain
CM2	Copilot
CRT	Cathode Ray Tube
CWS	Control Wheel Steering
ECAM	Electronic Centralized Aircraft Monitor
EEC	Electronic Engine Control

EFIS	Electronic Flight Instrument System
EGT	Exhaust Gas Temperature
EICAS	Engine Indicating and Crew Alerting System
F/D	Flight Director
FMA	Flight Mode Annunciator
FMC	Flight Management Computer
FMS	Flight Management System
G/A	Go-around
GPWS	Ground Proximity Warning System
ILS	Instrument Landing System
INS	Inertial Navigation System
IRS	Inertial Reference System
IRU	Inertial Reference Unit
LNAV	Lateral Navigation
LRU	Line Replaceable Unit
MCP	Mode Control Panel
MODE S:	When implemented, Mode S will provide the medium for a digital data link which will be used to exchange information between aircraft and various ATC functions and weather bases.
NAS	National Airspace System
NDB	Non-Directional Beacon
OMEGA	Enroute long-range radio navaid of very low frequency (VLF) hyperbolic type

C-3

PF	Pilot-Flying
PNF	Pilot-Not-Flying
PROF	Profile – used in vertical navigation
RVR	Runway Visual Range
TCAS	Traffic Alert and Collision Avoidance System
V/S	Vertical Speed
VHF	Very High Frequency
VNAV	Vertical Navigation
VOR	Very High Frequency (VHF) Omnidirectional Radio Range

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16. Abstract

Issues of flight deck automation are multifaceted and complex. The rapid introduction of advanced computer-based technology onto the flight deck of transport-category aircraft has had considerable impact both on aircraft operations and on the flight crew. As part of NASA's responsibility to facilitate an active exchange of ideas and information among members of the aviation community, a NASA/FAA/Industry workshop devoted to flight deck automation, organized by the Aerospace Human Factors Research Division of NASA Ames Research Center, was held in California in August 1988. Participants were invited from industry and from government organizations responsible for design, certification, operation, and accident investigation of transport-category, automated aircraft. The goal of the workshop was to clarify the implications of automation, both positive and negative. Workshop panels and working groups identified issues regarding the design, training, and procedural aspects of flight deck automation, as well as the crew's ability to interact and perform effectively with the new technology. The proceedings include the invited papers and the panel and working group reports, as well as the summary and conclusions of the conference.

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