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HUMAN FACTORS IN CNS/ATM SYSTEMS

The development of human-centred automation and
advanced technology in future aviation systems

*Approved by the Secretary General
and published under his authority*

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TABLE OF CONTENTS

	<i>Page</i>
Glossary	(ii)
Introduction	1
Historical background	1
Development of guidance material	2
Chapter 1. The ICAO CNS/ATM Concept	4
The CNS/ATM concept	4
The ICAO flight safety and Human Factors programme	6
Chapter 2. Automation in Future Aviation Systems	10
The role of the human operator in highly automated systems	10
CNS/ATM system automation	12
Issues and concerns in CNS/ATM systems automation	14
Chapter 3. Human-centred Technology	18
A concept of human-centred automation	18
Chapter 4. Principles of Human-centred Automation	21
Chapter 5. Qualities of Human-centred Automation	26
Appendix 1. Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation	33
Appendix 2. List of Recommended Reading	36

GLOSSARY

AERA	Automatic En-route Air Traffic Control	IFR	Instrument Flight Rules
AMSS	Aeronautical Mobile Satellite Service	ILS	Instrument Landing System
ANC	Air Navigation Commission (ICAO)	IMC	Instrument Meteorological Conditions
ADS	Automatic Dependence Surveillance	ISO	International Organization for Standardization
ASM	Air Space Management	LOFT	Line Oriented Flight Training
ATC	Air Traffic Control	MLS	Microwave Landing System
ATFM	Air Traffic Flow Management	NTSB	National Transport Safety Board (United States)
ATM	Air Traffic Management	OSI	Open Systems Interconnection
ATN	Aeronautical Telecommunication Network	RAIM	Receiver Autonomous Integrity Monitoring
ATS	Air Traffic Services	RNP	Required Navigation Performance
CNS	Communication, Navigation and Surveillance	SARPs	Standards and Recommended Practices and Procedures
CRM	Cockpit Resource Management	SSR	Secondary Surveillance Radar
FANS	Future Air Navigation Systems	TCAS	Traffic Collision Alerting System
GIB	GNSS Integrity Broadcast	VHF	Very High Frequency
GNSS	Global Navigation Satellite System	VMC	Visual Meteorological Conditions
ICAO	International Civil Aviation Organization		

INTRODUCTION

Historical background

1. The Tenth Air Navigation Conference (Montreal, 5-20 September 1991) “recognized the importance of Human Factors in the design and transition of future ATC systems”. It also “noted that automation was considered to offer great potential in reducing human error”. It further recommended that “work conducted by ICAO in the field of Human Factors pursuant to ICAO Assembly Resolution A26-9 include, *inter alia*, studies related to the use and transition to future CNS/ATM systems”.

2. Following the recommendation of the Conference, the ICAO Air Navigation Commission agreed that its task “Flight Safety and Human Factors” would be revised to include work on Human Factors considerations in future aviation systems with an emphasis on CNS/ATM-related human-machine interface aspects.

3. Based on the decision of the Commission, the Secretariat contacted experts from selected States and international organizations and reviewed recent and ongoing studies to identify Human Factors issues of relevance to ICAO CNS/ATM systems. The survey identified several areas in which application of Human Factors knowledge and experience would enhance future ICAO CNS/ATM systems safety and efficiency:

- **Automation and advanced technology in future ATS systems.** The application of state-of-the-art technology and automation is fundamental to the ICAO CNS/ATM concept. Experience shows that it is essential to take into account the human element during the design phase so that the resulting system capitalizes upon the relative strengths of humans and computer-based technology. This approach is referred to as a “human-centred” automation.
- **Flight deck/ATS integration.** ICAO CNS/ATM systems will provide for a high level of integration between aircraft and the air traffic control system. This will bring new and different challenges. The various components of the system will interact in new ways, and new means of communication between pilots and air traffic controllers will be available. A dedicated systems approach must be adopted to address the issues associated with this integration and to ensure that the system as a whole is “user-friendly”.
- **Human performance in future ATS.** The human element is the key to the successful implementation of the ICAO CNS/ATM concept. A broad base of scientific knowledge of human performance in complex systems is available and research continues to provide more. Additional research is still needed regarding the influence of organizational and management factors on individual and team performance in ATS. Information transfer in complex systems, the system-wide implications of data-link implementation, automated aids such as conflict prediction and resolution advisory systems, and the allocation of authority and functions between air and ground in future systems are areas in which guidance is necessary.
- **Training, selection and licensing of controllers.** Acquiring technical skills alone will not guarantee on-the-job performance with high reliability and efficiency. Resource management training programmes specially tailored to ATS requirements are under development. Although

some early attempts to address Human Factors training for controllers are in place, it is evident that much is lacking and more action in this regard is still desirable. Selection criteria which go beyond consideration of the candidate's technical aptitude and include social and personal characteristics associated with team performance are also important issues which are at the development stage. Licensing requirements which reflect these new training objectives would provide the framework to achieve them.

- **Safety monitoring of ATS activities.** Existing tools for monitoring safety may not be sufficient in view of the increased complexity and interdependence of the ICAO CNS/ATM activities. Guidance is needed on how ATS activities can be monitored to provide the information required for identifying and resolving safety issues.

Development of guidance material

4. This digest attempts to address the first of these issues utilizing experience gained from Human Factors knowledge. It presents the Human Factors implications of automation and advanced technology in future aviation systems, including CNS/ATM systems. It also intends to provide the civil aviation authorities with tools for establishing the requirements for the new systems and for reviewing proposals from manufacturers, from the perspective of Human Factors. The digest will also be useful for the ICAO panels and study groups working on the ICAO CNS/ATM concept to ensure that Human Factors principles are adequately considered during the development of automation and advanced technology in future systems. This digest will be followed by other digests addressing the remaining areas of CNS/ATM Human Factors concerns as enumerated above, as well as others which may emerge.

5. The discussion related to the recommendation of the Tenth Air Navigation Conference notes the potential of automation for reducing human error. There is, however, a concern among researchers, designers and users, that the indiscriminate application of automation may also create a whole new set of human errors. Experience gained in the operation of complex automated systems in civil aviation and elsewhere indicates that in order to be effective, automation must meet the needs and limitations of users and purchasers (i.e. civil aviation authorities). The digest aims at informing designers about the expected role of automation; assisting administrations in the evaluation of the equipment during the procurement process; and explaining to users what to expect from the tools which they will be given to achieve their tasks.

6. Experience gained with programmes developed outside civil aviation to meet the demands presented by complex systems (most notably in the nuclear power generation and chemical processing and weapons systems industries, all of which have characteristics in common with advanced aviation systems in terms of complexity and integration) is applied throughout the digest as necessary. These programmes were developed following the failure of projects which produced technically viable systems but which could not be maintained or operated effectively in the field; they ensure that high-technology systems take into account the relevant Human Factors aspects throughout the development cycle, along with the more traditional technical specifications. This is achieved by focusing attention on the operator's performance and reliability as part of the total system performance.

7. The ICAO Flight Safety and Human Factors programme activities already include issues related to air traffic control. Human Factors Digest No. 8 — *Human Factors in Air Traffic Control* (Circ 241) has recently been published and Human Factors issues related to CNS/ATM automation have been discussed at Flight Safety and Human Factors regional seminars. The Human Factors digests published by ICAO will help the reader to acquire better understanding of the generic Human Factors issues applicable throughout the aviation industry and the particular issues advocated by this document.

8. This digest includes the following:
- Chapter 1 introduces the historical background of the ICAO CNS/ATM system, discusses the concept and introduces the reader to the ICAO Flight Safety and Human Factors Programme.
 - Chapter 2 presents the role of automation in future aviation systems. It also discusses the role of the human operator in such a system. It is *essential* that system designers take the human element into account during the preliminary stages of system design. The chapter also discusses issues and concerns in CNS/ATM system automation.
 - Chapter 3 introduces the concept of *human-centred* automation, that is automation designed to work with human operators in pursuit of the stated objectives. Human-centred automation does not only enhance safety but also reduces training and operation costs by allowing efficient, effective and safe operation.
 - Chapter 4 introduces the principles of human-centred automation based on the premise that *a human (pilot, controller, etc.) bears the ultimate responsibility for the safety of flight operation.*
 - Chapter 5 introduces qualities human-centred automation should possess if it is to remain an effective and valued element of the aviation system. As automation becomes more complex, it will be increasingly difficult for human operators to remain aware of all actions being taken autonomously and thus increasingly difficult to know exactly what the automation is doing and why. Attributes of human-centered automation, capable of preventing such a situation from developing, are discussed in this chapter.
 - Appendix 1 presents ICAO policy on CNS/ATM systems implementation and operation.
 - Appendix 2 presents a list of recommended reading.

9. This digest was produced by the ICAO Secretariat with the assistance of the ICAO Flight Safety and Human Factors Study Group. It is based mainly on the work of Dr. Charles E. Billings, formerly of the Ames Research Centre, Moffett Field, California, on the subject of human-centred aircraft automation (NASA Technical Memorandum 103885, August 1991). It has also borrowed considerably from Harold E. Price's "Conceptual System Design and the Human Role", published in MANPRINT — *An Approach to System Integration*, edited by Harold R. Booher, Van Nostrand Reinhold, New York, 1990. Additional sources of information include ICAO Human Factors Digest No. 5 — *Operational Implications of Automation in Advanced Technology Flight Decks*, Human Factors Digest No. 8 — *Human Factors in Air Traffic Control* and ICAO Doc 9583 — *Report of the Tenth Air Navigation Conference*. The International Federation of Air Traffic Controllers (IFATCA) is also recognized for its detailed review of and feedback on the original draft.

Chapter 1

THE ICAO CNS/ATM CONCEPT

The CNS/ATM concept

1.1 By the end of the 1980s, ICAO as well as the entire aviation community had recognized the fundamental limitations of the existing air traffic system and the fact that the situation was going to get progressively worse. The characteristics and the capabilities of the present-day systems and of their implementation in various parts of the world revealed the following shortcomings in the present communications, navigation and surveillance (CNS) systems:

- a) the propagation limitations of current line-of-sight systems and/or accuracy and reliability limitations imposed by the variability of propagation characteristics of other systems;
- b) the difficulty in large parts of the world, for a variety of reasons, in implementing present CNS systems and operating them in a consistent manner; and
- c) the limitations of voice communications and the lack of digital air-ground data interchange systems to support modern automated systems in the air and on the ground.

1.2 Although the effects of these limitations are not the same for every part of the world, it is evident that one or more of these factors inhibit the further development of air navigation almost everywhere. It was obvious that new CNS systems which would permit the proper development of an improved air traffic control system should be developed.

1.3 At the end of 1983, the ICAO Council established the Future Air Navigation Systems (FANS) Committee to study, identify and assess new concepts and new technology in the field of air navigation, including satellite technology, and to make recommendations thereon for the development of air navigation on a global basis.

1.4 The FANS Committee completed its task and presented its findings and recommendations to ICAO's Tenth Air Navigation Conference, held in Montreal from 5 to 20 September 1991. It concluded that the exploitation of satellite technology appeared to be the only viable solution to overcome the shortcomings of the existing CNS system and also fulfil the global needs and requirements of the foreseeable future. The committee developed an over-all long-term projection for the co-ordinated evolutionary development of air navigation for international civil aviation over a period of the order of 25 years, in which, complementary to certain terrestrial systems, satellite-based CNS systems will be the key to world-wide improvements.

1.5 The main features of the global concept of the new CNS/ATM system are:

Communications

- In the future, aeronautical mobile communication will make extensive use of digital modulation techniques to permit high-efficiency information flow, optimum use of automation both in the

aircraft and on the ground, and economical frequency spectrum utilization. Except for high-density areas within coverage of terrestrial-based communications systems, aeronautical mobile communications services (data and voice) will use satellite relay, operating in the frequency bands allocated to the aeronautical mobile satellite service (AMSS). Terrestrial-based air-ground communication will continue to serve in terminal areas and in other high-density airspace.

- VHF will remain in use for voice and certain data communication in many continental and terminal areas. However, steps should be taken to preclude future saturation.
- The SSR Mode S will provide an air-ground data link which will be used for ATS purposes in high-density airspace. Interoperability with other data links will be facilitated through the application of the open systems interconnection (OSI) model.
- The aeronautical communication network (ATN) concept, through the use of an agreed communication protocol structure, will provide for the interchange of digital data packets between end-users of dissimilar air-ground and ground-ground communication sub-networks.

Navigation

- Area navigation (RNAV) capability will be progressively introduced in compliance with the required navigation performance criteria. Studying the modern developments in aircraft navigation systems, the committee identified that the method most commonly used at present, i.e. requiring mandatory carriage of certain equipment, constrained the optimum application of modern airborne equipment. Now that new navigation aids (notably satellites) are available, it will be possible for aircraft operators to select, from among competing systems, the one that is most adaptable to their needs. To enable that flexibility and to support the development of more flexible route systems and RNAV environment, the concept of required navigation performance (RNP) has been developed. This concept is very similar, in principle, to the minimum navigation performance specification (MNPS) concept now in use in North Atlantic and northern Canadian airspace. Both concepts enable a required navigational performance to be achieved by a variety of navigation equipment; however, as distinct from MNPS, RNP is primarily intended for application in airspace where adequate surveillance is available to air traffic control (ATC).
- Global navigation satellite systems (GNSS) will provide world-wide coverage and will be used for aircraft navigation and for non-precision type approaches. Systems providing independent navigation, where the user performs on-board position determination from information received from broadcast transmissions by a number of satellites, will potentially provide highly reliable and accurate and high-integrity global coverage and could meet the navigation system requirements for sole means of navigation for civil aviation.
- The present radio navigation systems serving en-route navigation and non-precision approaches will be able to meet the RNP conditions and coexist with satellite navigation systems. However, it is foreseen that satellite systems will eventually become the sole means of radio navigation. The timing of withdrawal of the present terrestrial systems will depend on many factors, among which the implementation and quality of the new systems will be prominent.

Surveillance

- Secondary surveillance radar (SSR) will remain in wide use in many parts of the world. By enhancing SSR with Mode S, the selective address and data link capabilities will further enhance the beneficial role of SSR for surveillance purposes.
- Automatic dependent surveillance (ADS) will be used mainly in non-radar coverage areas. ADS is a function in which aircraft automatically transmit, via a data link, data derived from on-board navigation systems. As a minimum, the data include aircraft identification and three-dimensional position. Additional data may be provided as appropriate. The introduction of air-ground data links, together with sufficiently accurate and reliable aircraft navigation systems, presents the opportunity to provide surveillance services in areas which lack such services in the present infrastructure, in particular oceanic areas and other areas where the current systems prove difficult, uneconomical or even impossible to implement. In addition to areas which are at present devoid of traffic position information other than the pilot-provided position reports, ADS will find beneficial application in other areas, including high-density areas, where it may serve as an adjunct to or backup for secondary surveillance radar and thereby reduce the need for primary radar.

Air traffic management (ATM)

- The term air traffic management (ATM) is used to describe the airspace and traffic management activities carried out in a co-operative manner by the aeronautical authorities concerned with planning and organizing the effective use of the airspace and air traffic flows within their area of responsibility. ATM consists of a ground part and an air part, where both parts are integrated through well defined procedures and interfaces. The ground part of ATM comprises air traffic services (ATS), air traffic flow management (ATFM) and airspace management (ASM). The general objectives of ATM are to enable aircraft operators to meet their planned times of departure and arrival and adhere to their preferred flight profiles with minimum constraints and without compromising the agreed level of safety. The goals of the ATM system are to maintain or increase the existing level of safety, to accommodate different types of equipped aircraft, to increase system capacity and to minimize delays through the realization of an efficient use of the airspace.

1.6 The ICAO CNS/ATM systems concept is widely seen as advantageous because it permits the enhancement of safety. Improved reliability of the aeronautical mobile satellite communications system, for example, will mean more complete and less interrupted ATS communications in some parts of the world. In addition, ADS and data communications systems facilitate improved conflict detection and resolution and assist the controller by providing advice on conflict resolution. More rapid and detailed information on weather warnings such as storm alerts will also contribute to the safety and effectiveness of flight operations. Further, the concept introduces air traffic management improvements which will permit more flexible and efficient use of airspace. A global introduction of the ICAO CNS/ATM concept can, within a short period, achieve a system which is capable of balancing the advantages of both strategical planning and short-term tactical control, thereby enhancing flight safety and efficient airspace utilization world-wide.

The ICAO flight safety and Human Factors programme

1.7 In 1986, ICAO set the foundations for the development of a programme on Human Factors as follows: *to improve safety in aviation by making States more aware of and responsive to the importance of*

Human Factors in civil aviation through the provision of practical Human Factors materials and measures developed on the basis of experience within States. Simultaneously, the ICAO Flight Safety and Human Factors Group was established, composed with experts from a wide range of the international aviation community in terms of background, professional interests and geographical representation.

1.8 Human Factors is a wide and complex field of endeavour. There are widespread international variations in the degree of application or influence of its various component disciplines, namely medicine, social/behavioural sciences, and engineering. While in some parts of the world Human Factors is a synonym for aviation medicine, in others it is strongly based in engineering or ergonomics. Lately, greater emphasis has been placed in the social and behavioural sciences by certain sectors of the community. This was a much needed and welcomed development. Without focusing on the relative merits of each different approach, the integration of the most valuable aspects of each of them was a major objective.

1.9 Initially, the ICAO programme was divided into four distinct phases. They complement each other and there is some reasonable overlapping between them.

1.10 The *initial phase* involved the search for a balanced approach to Human Factors. The balance is necessary as a consequence of the nature of ICAO and the multidisciplinary nature of Human Factors. ICAO represents the interests and — ultimately — the consensus of more than 180 Contracting States in the international aviation community. Needless to say, consensus in such a multicultural environment is sometimes difficult to achieve.

1.11 The *awareness phase* is a major building block for the programme and a stepping stone to the following phases. There are many parts of the world where the notion of Human Factors is, to say the least, not very well understood. Many segments of the community simply ignore it, following the well established misconception that discipline is the key to safety. Others pretend that “soft” issues have no place in aviation. There are also those who contend that people in the aviation industry are too technically oriented to understand the language — let alone the proposals — of Human Factors. Although the fragility of such contentions is obvious, they do reflect facts — as well as intellectual biases — which cannot be ignored. It is unreasonable to expect any significant progress in the Human Factors programme unless a clear statement is delivered about the operational relevance of Human Factors to aviation safety.

1.12 The means selected to deliver the message is a series of digests dealing with different aspects of Human Factors and how they relate to flight safety. The first ten digests were:

- Digest No. 1 — *Fundamental Human Factors Concepts* (Circular 216);
- Digest No. 2 — *Flight Crew Training: Cockpit Resource Management (CRM) and Line-Oriented Flight Training (LOFT)* (Circular 217);
- Digest No. 3 — *Training and Operational Personnel in Human Factors* (Circular 227);
- Digest No. 4 — *Proceedings of the ICAO Human Factors Seminar* (Circular 229);
- Digest No. 5 — *Operational Implications of Automation in Advanced Technology Flight Decks* (Circular 234);
- Digest No. 6 — *Ergonomics* (Circular 238);
- Digest No. 7 — *Investigation of Human Factors in Accidents and Incidents* (Circular 240);

- Digest No. 8 — *Human Factors in Air Traffic Control* (Circular 241);
- Digest No. 9 — *Proceedings of the Second ICAO Flight Safety and Human Factors Global Symposium* (Circular 243); and
- Digest No. 10 — *Human Factors, Management and Organization* (Circular 247).

1.13 Other means deemed appropriate to this phase include articles in the *ICAO Journal* and other media; participation by members of the Secretariat and the Study Group in events organized by other international bodies to “spread the gospel”, and assistance to national administrations and other organizations in the preparation of Human Factors-related events.

1.14 The *educational phase* is at the heart of the programme. It is important to distinguish between *education* and *training*, to preclude misunderstandings about the role of ICAO in this programme, and to provide justification of the means selected. It is also relevant because most aviation people are involved in training and might confuse the terms, thus creating false expectations.

1.15 Education involves the acquisition of a set of knowledge, values, attitudes and skills upon which specific job abilities can be acquired later. Training is the process of developing specific skills, knowledge and attitudes. Education is thus the precursor of training. ICAO’s mission is to present the international aviation community with the means (i.e. education) to facilitate the development of particular job-related skills, knowledge and attitudes (i.e. training) of different personnel. The hands-on training is the exclusive responsibility of the civil aviation administrations, the operators and the manufacturers.

1.16 The first step in achieving the educational objectives of the programme was the organization of regional seminars. Five regional seminars have so far been held: Douala (Cameroon), Bangkok (Thailand), Mexico City (Mexico), Cairo (Egypt) and Rio de Janeiro (Brazil), and two more are planned for 1994, one in the European region and one in the Eastern and Southern African region. These four- or five-day seminars address Human Factors issues covered by the series of digests in addition to Human Factors issues which are of particular concern to the region.

1.17 A world-wide symposium is held every three years. The first symposium was held in Leningrad from 3 to 7 April 1990, under the auspices of the Ministry of Civil Aviation of the USSR. The programme of regional seminars is one of the recommendations from Leningrad. The second symposium was held in Washington, D.C. from 12 to 15 April 1993, at the invitation of the United States Government. The theme of the symposium was “Human Factors Training for Operational Personnel”.

1.18 The consolidation of the digests into a single document — an ICAO Human Factors training manual — will fulfil the twin objectives of presenting the community with a standardized training package as well as a single source of reference to comply with the Human Factors requirements included in Annex 1, Eighth Edition, while allowing for its periodic revision and updating.

1.19 The last phase of the programme, the *regulatory phase*, presents some contentious issues. The essence of ICAO is regulation; however, in Human Factors, regulation is a topic which eludes objectivity and introduces contrasting points of view, lively discussions and heated arguments. The approach to regulation in the Human Factors field is subject to social, cultural, and even philosophical practices and preferences, and is also influenced by intellectual biases. As with the approach to Human Factors, consensus on a world-wide basis is difficult — if not impossible — to obtain. Unless sound judgement is exercised, there is the risk that the end result might be, perforce, a compromise.

1.20 However, as a result of the gradual acceptance of Human Factors as a hard-core technology by the international community during the last few years, the development of broad and general regulations on Human Factors in the form of Standards and Recommended Practices (SARPs) and procedures in ICAO Annexes other than Annex 1 has now become both possible and desirable. The most effective way envisaged to achieve this goal is to review all ICAO Annexes to identify those where the inclusion of Human Factors SARPs would be appropriate.

1.21 As in the search for a balanced approach to Human Factors, it is not for ICAO to assume the arbitrator's role and pronounce right from wrong in the different approaches to regulation. However, some simple principles, widely recognized by regulatory agencies, can be applied to shed some light on this issue. They include:

- Regulation shall not be a substitute for good judgement.
- Over-regulation is as dangerous as no regulation.
- Regulations should be developed only when the problem is well known, and when workable solutions have been identified and accepted.

1.22 ICAO's endeavour in the Human Factors issues related to the CNS/ATM systems are of an educational or awareness-raising nature. This digest, therefore, does not purport to be a designer's handbook, nor does it attempt to cover the myriad details of Human Factors engineering that determine how a workstation should be designed. Rather it has the sole objective of suggesting questions that should be answered *before* beginning the design of the workstation or equipment.

Chapter 2

AUTOMATION IN FUTURE AVIATION SYSTEMS

The machine does not isolate man from the great problems of nature but plunges him more deeply into them.

Antoine de Sainte-Exupéry

2.1 One major issue in future aviation systems (including the CNS/ATM system) is the impact of automation and the application of advanced technology on the human operator. In order to be effective, automation must meet the needs and constraints of designers, purchasers (i.e. civil aviation authorities) and users. It is, therefore, essential to provide guidelines for the design and use of automation in highly advanced technology systems including the CNS/ATM system. What roles should automation play in future systems, how much authority should it have, how will it interact with the human operator and what role should be reserved for the human are but a few of the many questions that are now being advanced and should be answered during conceptual system design.

The role of the human operator in highly automated systems

2.2 Technology has advanced to an extent for computers (automation) to be able to perform nearly all of the continuous air traffic control and surveillance as well as aircraft navigational tasks of the aviation system. Why, then, is the human needed in such systems? Couldn't automation be constructed to accomplish all the discrete tasks of the human operator? Would it not be easier and even cheaper to design highly reliable automata that could do the entire job without worrying about accommodating a human operator?

2.3 Many system designers view humans as unreliable and inefficient and think that they should be eliminated from the system. (This viewpoint is fuelled by the promise of artificial intelligence and recently introduced advanced automation.) It is unrealistic to think that machine functioning will entirely replace human functioning.¹ Automation is almost always introduced with the expectation of reducing human error and workload, but what frequently happens is that the potential for error is simply relocated. More often than not, automation does not replace people in systems; rather, it places the person in a different, and in many cases, more demanding role.²

2.4 The aviation system consists of many variables that are highly dynamic and not fully predictable. Real-time responses to developing situations are what assure the safe operation of the whole aviation system. The basic difference in the way humans and computers respond to situations could mean the difference between a reliable (safe) and an unreliable (unsafe) aviation system. Human response involves the use and co-ordination of eyes, ears and speech and the ability to respond to unexpected problems through

1. For further discussion on this topic, see Harold E. Price, "Conceptual System Design and the Human Role", in *MANPRINT*, Harold R. Booher (ed.), Van Nostrand Reinhold, New York, 1990.
2. Bainbridge, L., "Ironies of Automation", in *New Technology and Human Error*, J. Rasmussen, K. Duncan and J. Lepalt (eds.). John Wiley and Sons Ltd., 1987.

initiative and common sense. Automation (computers) rely on the *right programme* being installed to ensure that the *right action* is taken at the *right time*. The inability of automation designers to engineer a programme that can deal with all presumed eventualities and situations in the aviation system, and the uncontrollable variability of the environment are some of the major difficulties of computerizing all the tasks of the aviation system. The reality is: if automation is faced with a situation it is not programmed to handle, it fails. Automation can also fail in unpredictable ways. Minor system or procedural anomalies can cause unexpected effects that must be resolved in real time, as in the air traffic control breakdown in Atlanta, Georgia (U.S.A.) terminal airspace in 1980 and the breakdown of telecommunication systems in New York in 1991. Considering these limitations, it is not very difficult to see that an automation-centred aviation system can easily spell disaster to the whole aviation infrastructure.

2.5 Although humans are far from being perfect sensors, decision-makers and controllers, they possess several invaluable attributes, the most significant of which are: their ability to reason effectively in the face of uncertainty and their capacity for abstraction and conceptual analysis of a problem. Faced with a new situation, humans, unlike automatons, do not just fail; they cope with the situation and are capable of solving it successfully. Humans thus provide to the aviation system a degree of flexibility that cannot now and may never be attained by computational systems. Humans are *intelligent*: they possess the ability to respond quickly and successfully to new situations. Computers, the dominant automatons of the ATC system, cannot do this except in narrowly defined, well understood domains and situations.³

2.6 Automation should be considered to be a tool or resource, a device, system or method which enables the human to accomplish some task that might otherwise be difficult or impossible, or which the human can direct to carry out more or less independently a task that would otherwise require increased human attention or effort. The word “tool” does not preclude the possibility that the tool may have some degree of intelligence — some capacity to learn and then to proceed independently to accomplish a task. Automation is simply one of many resources available to the human operator, who retains the responsibility for management and direction of the over-all system. This line of thinking has been well understood and precisely defined by the aviation Human Factors community, to the extent that philosophies have been developed by some organizations in the industry to demarcate the function and responsibilities of the two elements (human operators and automation) in the system. A very good example of such a philosophy as adopted by one operator states:⁴

The word “automation”, where it appears in this statement, shall mean the replacement of a human function, either manual or cognitive, with a machine function. This definition applies to all levels of automation in all airplanes flown by this airline. The purpose of automation is to aid the pilot in doing his or her job.

The pilot is the most complex, capable and flexible component of the air transport system, and as such is best suited to determine the optional use of resources in any given situation.

Pilots must be proficient in operating their airplanes in all levels of automation. They must be knowledgeable in the selection of the appropriate degree of automation, and must have the skills needed to move from one level of automation to another.

3. For further discussion on this topic, see Wiener, E.L. and D.C. Nagel, “Human Factors in Aviation, Section Two: Pilot Performance”. San Diego, Academic Press, Inc., 1988; and Cooley, M.J.E., “Human Centered Systems: An Urgent Problem for System Designers”. AI and Society 1, 1987.

4. Delta Airlines. “Statement of Automation Philosophy”.

Automation should be used at the level most appropriate to enhance the priorities of Safety, Passenger Comfort, Public Relations, Schedule and Economy, as stated in the Flight Operations Policy Manual.

In order to achieve the above priorities, all Delta Air Lines training programs, training devices, procedures, checklists, aircraft and equipment acquisitions, manuals, quality control programs, standardization, supporting documents and the day-to-day operation of Delta aircraft shall be in accordance with this statement of philosophy.

2.7 Introducing such an automation philosophy into aviation operations is beneficial since by defining how and when automation is to be used, it demarcates the boundary of human-machine responsibilities and thus promotes safety and efficiency in the system.

CNS/ATM system automation

2.8 The core of the benefits of the CNS/ATM system will be derived from automation intended to reduce or eliminate constraints imposed on the system. Data bases describing current and projected levels of demand and capacity resources, and sophisticated automated models that accurately predict congestion and delay will, in the future, be used to formulate effective real-time strategies for coping with excess demand. Automation will play a central role in establishing negotiation processes between the aircraft flight management computer systems and the ground-based air traffic management process, to define a new trajectory that best meets the user's objective and satisfies ATM constraints. The human operator, however, should decide the outcome of the negotiation and its implementation. Similarly, when the ground-based management process recognizes a need to intervene in the cleared flight path of an aircraft, the ATM computer will negotiate with the flight management computer to determine a modification meeting ATM constraints with the least disruption to the user's preferred trajectory. Automation can also probe each ADS position-and-intent report from an aircraft to detect potential conflicts with other aircraft, with hazardous weather or with restricted airspace.

2.9 The range of use of automated systems and automation is so central to the CNS/ATM systems that it will not be possible to derive the envisaged benefits of the CNS/ATM system or even implement it effectively without the use of automation. It is clear that the possibilities being researched as a result of the introduction of the global CNS/ATM system range well beyond what is strictly envisaged at present and further development may strictly depend on more and more automation.

2.10 Automation has been gradually introduced in the aviation system. Flight deck automation has made aircraft operations safer and more efficient by ensuring more precise flight manoeuvres, providing display flexibility, and optimizing cockpit space. Many modern ATC systems include automated functions, for example in data gathering and processing, which are fully automated with no direct human intervention. Computerized data bases and electronic data displays have enhanced data exchange, the introduction of colour radar systems have allowed a greater measure of control and the computerization of Air Traffic Flow Management (ATFM) has proved to be an essential element to efficiently deal with the various flow control rates and increases in traffic demand.

2.11 For the purpose of this digest, automation refers to *a system or method in which many of the processes of production are automatically performed or controlled by self operating machines, electronic*

*devices, etc.*⁵ The concern is with automation of future aviation-related technology and in particular with Human Factors issues in CNS/ATM systems development and application. Automation is essential to the progressive evolution of the CNS/ATM systems and is expected to play a commanding role in future development of aviation technology. As such, its progressive introduction, therefore, is most desirable.

2.12 The techniques of air traffic management are constantly changing. New data link and satellite communication methods are evolving, the quality of radar and data processing is improving, collision avoidance systems are being developed, direct routing of aircraft between departure and arrival airports instead of via airways is being explored, and future air navigation systems are being researched and developed. More and more possibilities intended to increase the benefits of the concept in a wider scale are also being discovered and introduced.

2.13 Further options offered by such technological advances have to be considered in terms of safety, efficiency, cost effectiveness and compatibility with human capabilities and limitations. These advances change the procedures and practices of the global aviation system, the working environment and the role of pilots, air traffic controllers, dispatchers, aircraft maintenance technicians, etc., presenting all involved with the challenge not to overlook the Human Factors issues involved. Whenever significant changes to operational procedures or regulations are contemplated, a system safety analysis must be conducted. The objective of such analysis is to identify any safety deficiencies in the proposed changes before they are implemented, and to ensure that the new procedures are *error tolerant* so that the consequences of human or technological failure are not catastrophic. Human Factors consideration in the design and development of new systems can assure that the paramount requirement of safety is never compromised in the whole system, but maintained and enhanced throughout all future challenges.

2.14 Development in CNS/ATM systems will seek to do more with less, by designing and procuring air traffic management systems that are highly automated. Increased automation in aviation is inevitable. The issue is therefore about *when, where* and *how* automation should be implemented, not *if* it should be introduced. Properly used and employed, automation is a great asset. It can aid efficiency, improve safety, help to prevent errors and increase reliability. The task is to ensure that this potential is realized by matching automated aids with human capabilities and by mutual adaptation of human and machine to take full advantage of the relative strengths of each. In aviation automated systems, the human (pilot, controller, etc.), who is charged with the ultimate responsibility for the safe operation of the system must remain the key element of the system: automation or the machine must assist the human to achieve the over-all objective, never the contrary.

2.15 A major design challenge in the development of air traffic management procedures and techniques using new technologies is to realize system improvements that are centred on the human operator. Information provided to the human operator and the tasks assigned must be consistent with the human's management and control responsibilities as well as the innate characteristics and capabilities of human beings. Any future technological advance in the aviation system, including the CNS/ATM system, should therefore take into account the human-machine relationship early in its design process and development. If account is not taken at this stage, the system may not be used as intended, prejudicing the efficiency or safety of the whole system. Automation must be designed to assist and augment the capabilities of the human managers; it should, as much as possible, be *human-centred*. As basic understanding of Human Factors improves, and as facilities for testing the Human Factors aspects of system designs become available, the design process can be expected to be easier.

5. See ICAO Human Factors Digest No. 5 — *Operational Implications of Automation in Advanced Technology Flight Decks* for other definitions of automation as used in the digest.

Issues and concerns in CNS/ATM systems automation

2.16 CNS/ATM systems are intended to be a world-wide evolution of communications, navigation and surveillance techniques into a largely satellite-based system. As such, they entail a continuous increase of the level of automation in aviation operations. Optimum use of automation both in the aircraft and on the ground (air traffic control, dispatch and maintenance) is desired to permit high efficiency information flow. The Automatic Dependence Surveillance data will be used by the automated air traffic management system to present a traffic display with as much information as possible to the operator. To increase capacity and reduce congestion, airports and airspaces must be treated as an integrated system resource, with optimal interaction between system elements, aircraft, the ground infrastructure, and most importantly, the human operators of the system.

2.17 In some States, extensive research is being done on improvements to air safety through the introduction of air-ground data links replacing the majority of pilot/controller voice communications. It should, however, be recognized that voice communication will still be required, at least for emergency and non-routine communications. Automation is considered to offer great potential in reducing human error while providing for increased airspace capacity to accommodate future growth in air traffic. This, however, could involve changes in the human-machine interface which in the future may include increased use of artificial intelligence to assist the pilot and the controller in the decision-making process.

2.18 All forms of an automated assistance for the human operator must be highly reliable, but this may also induce complacency. Human expertise may gradually be lost and if the machine fails, the human operator may accept an inappropriate solution or become unable to formulate a satisfactory alternative. The most appropriate forms of human-machine relationship depend on the type of task which is automated and particularly on the interaction between planning and executive functions.

2.19 In the air traffic management environment, it is highly accepted that the performance of routine ATC tasks aids memory, which is not the case if these tasks are done automatically for the controller. Recent studies have shown that, in order to form a mental picture of the traffic situation, controllers derive a lot of their situational awareness by speaking to the aircraft and by making annotations on paper strips or making inputs (in more automated systems).⁶ Verbal and written (or keyboard) inputs keep people “in the loop” and allow active updating of the mental picture and situational awareness in its widest sense.⁷ It is believed that the automation of data can lead to deficiencies in human performance, since it can deprive the controller of important information about the reliability and durability of information. Automation may well reduce the effort required to perform certain tasks and the stress associated with them, but may also lead to loss of job satisfaction by taking away some of the intrinsic interests of the job, and the perceived control over certain functions.

2.20 There is enough information, both from safety deficiencies information systems and from accident reports, to illustrate the impact of the technology-centred approach to automation. More than 60 concerns relating to automation were identified by a subcommittee of the Human Behaviour Technology

6. Dr. A. Isaac, “Imagery Ability and Air Traffic Control Personnel”, paper presented at the New Zealand Psychology Conference — Aviation Psychology Symposium. Massey University, Palmerston North, 1991.

7. Another study (in the United States) in cognitive psychology suggests that processing data on multiple levels (physical manipulation and repetition are two examples) should improve memory for the information being processed. However, limited information is available about how this process works in ATC and whether automation will have a negative impact on memory for flight data.

Committee established by the Society of Automotive Engineers (SAE) to consider flight deck automation in 1985. These concerns were grouped into nine categories, the majority of which are as relevant to the air traffic control environment as they are to the flight deck. A brief presentation of such concerns includes:⁸

- **Loss of systems awareness** may occur when the human operator is unaware of the basic capabilities and limitations of automated systems, or develops erroneous ideas of how systems perform in particular situations.
- **Poor interface design.** Automation changes what is transmitted through the human-machine interface, either leading to some information not being transmitted at all or the format of the transmitted information being changed. Traditionally, most information has been conveyed from the machine to the human by means of visual displays and from the human to the machine by means of input devices and controls. Poor interface design may also combine with the time required for the human to take over from automation and may become an important factor, by reducing the quality of execution or practice of an event due to lack of warmup.
- **Attitudes towards automation** could best be expressed as an indication of frustration over the operation of automated systems in a non user-friendly environment, although improvements in the human-machine interface would probably reduce this feeling to some extent. Wherever introduced, automation has not been uncritically accepted by those who are meant to operate it. Some aspects of automation are accepted while others are rejected (in some cases because operators did not operate the equipment acceptably in the real world environment). Acceptance of automation may also be affected by factors related to the culture of the organization to which employees belong. Poor relationships with management, employee perceptions of having had no choice in the decision to accept automation, and lack of involvement in the development of automation are other examples of factors that may negatively affect the acceptance of automation. These factors may operate independently of the quality of the automation provided to the employees.
- **Motivation and job satisfaction** involve problem areas such as loss of the controller's feeling of importance, the perceived loss in the value of professional skills, and the absence of feedback about personal performance. Many operators feel that their main source of satisfaction in their job lies in its intrinsic interest to them. They believe that the challenge of the job is one of the main reasons they enjoy their profession. A takeover by automation to the point that job satisfaction is reduced can lead to boredom and general discontent.
- **Over-reliance** on automation occurs because it is easy to become accustomed to the new automated systems' usefulness and quality. A tendency to use automation to cope with rapidly changing circumstances may develop even when there is not enough time to enter new data into the computer. When things go wrong, there may also be a reluctance by the human to discard the automation and take over.
- **Systematic decision errors.** Humans may depart from optimal decision-making practices, particularly under time pressure or other stress. The existence of human biases may further limit the ability of humans to make optimal decisions. One approach to reduce or eliminate biased decision-making tendencies is to use automated decision-making aids at the time decisions are required. In such a system, humans adopt one of two strategies: accept or reject

8. For a full discussion of these concerns, refer to ICAO Human Factors Digest No. 5 — *Operational Implications of Automation in Advanced Technology Flight Decks* (Circular 234).

the machine recommendation. Although benefits of automated decision making aids are theoretically evident, they still remain to be conclusively demonstrated.

- **Boredom and automation complacency** may occur if a major portion of air traffic management is completely automated, and human operators are lulled into inattention. In the particular case of complacency, humans are likely to become so confident that the automatic systems will work effectively that they become less vigilant or excessively tolerant of errors in the system's performance.
- **Automation intimidation** results in part because of an increase in system components. The result is a reliability problem, since the more components there are, the more likely it will be that one will fail. However, humans remain reluctant to interfere with automated processes, in spite of some evidence of malfunction. This is partly due to inadequate training and partly to other pressures.
- **Distrust** normally occurs because the assessment of a particular situation by the human differs from the automated system. If the system does not perform in the same manner as a human would do, or in the manner the controller expects, it can lead to either inappropriate action or concern on the part of the human. This can also occur if the human is not adequately trained. Distrust can be aggravated by flaws in system design which lead to nuisance warnings.
- **Mode confusion and mode misapplication** are results of the many possibilities offered by automation, as well as of inadequate training. It is possible with a new computer technology for the controller to assume that the system is operating under a certain management mode when in fact it is not.
- **Workload.** The advance of automation has been based partly on the assumption that workload would be reduced, but there is evidence to suspect that this goal has yet to be achieved. In the air traffic control environment, additional working practices such as data entry/retrieval methods may actually increase workload. For example, merely automating certain aspects of an ATC system will not necessarily enable the air traffic control officer to handle more traffic. Automation should be directed at removing non-essential tasks, thereby allowing the controller to concentrate on more important tasks, such as monitoring or directly controlling the system.
- **Team function.** The team roles and functions in automated systems differ from those which can be exercised in manual systems. As an example, controllers in more automated systems are more self-sufficient and autonomous and fulfil more tasks by interacting with the machine rather than with colleagues or with pilots. There is less speech and more keying. This affects the feasibility and development of traditional team functions such as supervision, assistance, assessment and on-the-job training. When jobs are done by members of closely co-ordinated team, a consensus about the relative merits of individual performance can form the basis not only of professional respect and trust but also of promotions or assignments of further responsibilities.

2.21 Technology-centred approach in the automation of highly advanced technologies such as the nuclear power plant industry, chemical industry, civil aviation, space technology, etc., resulted in accidents with a great loss of lives and property. Basically, such accidents were an outcome of human-machine incompatibilities. Since the technology was easily available, engineering-based solutions to human error were

implemented without due consideration of human capabilities and limitations. Technology-centred automation may be based on the designer's view that the human operator is unreliable and inefficient, and so should be eliminated from the system. However, two ironies of this approach have been identified:⁹ one is that designer errors can be a major source of operating problems; the other is that the designer who tries to eliminate the operator still leaves the operator to do the tasks which the designer does not know how to automate. To this we can add the fact that automation is not, after all, infallible and usually fails in mysterious and unpredictable ways. It is for this reason that there are increasing calls for a human-centred approach which takes all the elements, and especially the human element, into due consideration. Hard lessons have been learned in the automation of aviation systems in the past. Cockpit automation stands as an example. However, in cockpit automation, we can now say that — albeit with notorious exceptions — there is a return to human-centred automation, which is a positive and encouraging trend strongly endorsed by ICAO. It is hoped that lessons learned in the past are applied to all new advanced technology systems so that same mistakes will not be committed.

9. Bainbridge, L., "Ironies of Automation", in *New Technology and Human Error*, J. Rasmussen, K. Duncan and J. Lepalt (eds.). John Wiley and Sons Ltd., 1987.

Chapter 3

HUMAN-CENTRED TECHNOLOGY

A concept of human-centred automation

3.1 “Human-centred automation” is a systems concept, meaning *automation designed to work cooperatively with human operators in pursuit of the stated objectives*. Its focus is an assortment of automated systems designed to assist human operators, controllers, or managers to meet their responsibilities. The quality and effectiveness of the human-centred automation system is a function of the degree to which the combined system takes advantage of the strengths and compensates for the weaknesses of both elements. To better understand the concept of human-centred automation we may define a fully autonomous, robotic system as non-human-centred — the human has no critical role in such a system once it is designed and is made operational. Conversely, automation has no role to play in a fully manual system.

3.2 None of today’s complex human-machine systems are at either extreme. Nearly all systems provide automatic devices to assist the human in performing a defined set of tasks, and reserve certain functions solely for the human operator. No one expects future advanced aviation systems to be fully robotized, discarding the human element in its operation. It is also not expected to be operated without the assistance of some kind of automation. In fact, even today, both humans and machines are responsible for the safe operation of the aviation system. As was discussed in the previous chapter, future growth in the aviation system will require more automation. Technology advancement in the system may well be based on the way we handle information and utilize automation. Information technology in aviation systems will foster profound changes in areas such as communications (air/ground, air/air, ground/ground), panel displays (flat, head-up, head-down), voice interactive techniques, data link, etc. Automation technology will likewise foster significant progress in areas such as flight control, air traffic control, digital control systems, fly by wire, etc.

3.3 The trend toward more information, greater complexity and more automated operation have the potential to isolate the human operators from the operation and to decrease their awareness of the state and situation of the system being operated. There are many reasons, several of which were discussed earlier, why system designers should consider Human Factors from the very beginning of the design process. Investigations of all major accidents which have occurred within the last two decades in organizations using highly advanced technology (Three Mile Island and Chernobyl — nuclear power technology, Tenerife — civil aviation, Bhopal — chemical industry, Challenger — space technology) showed that improper or flawed interfaces between human operators and technology were among the causal factors. Human error in those accidents was induced by poor design, flawed procedures, improper training, imperfect organizations, or other systemic deficiencies. The key issue here is that human error or degraded human performance is induced by factors which can be avoided at the proper stage.¹ Systems design which might induce human error can be avoided by better Human Factors design decisions from the very beginning of system design to the very end.

1. For further reading on this subject, see Perrow, C., *Normal Accidents: Living with High-risk Technologies*. Basic Books Inc., New York, 1984.

3.4 The goal of human-centred automation is to influence the design of human-machine systems in advanced technology so that human capabilities and limitations are considered from the early stages of the design process, and are accounted for in the final design. A design that does not consider Human Factors issues can not result in an optimal system that enhances productivity, safety and job satisfaction. Lack of recognition of the unique benefits to be derived from human-centred automation may perhaps be the main reason why Human Factors technology has seldom been applied early or integrated routinely into the system design process. There are, however, several very important payoffs for early investment in Human Factors.²

Human-centred technology (automation) prevents disasters and accidents

3.5 Human or operator error has arguably been identified as the primary causal factor of accidents and incidents. Speaking of systems in general, about 60 to 80 per cent of accidents are attributed to human error.³ However, recent research applied to accident investigations casts doubt on such findings, by demonstrating that in most cases where human operators are said to be the primary causal factor of an accident, they are confronted by unexpected and unusually opaque technological interactions resulting in unforeseen failures. Analysis of several high-technology accidents, initially attributed to human error, reveals that most of the human error identified is induced by other factors. It is therefore essential to differentiate systemic-induced human errors from those which are truly the consequence of deficient performance. Accident-inducing factors include poor hardware design, poor human-machine integration, inadequate training, and poor management practices and flawed organizational design. Those factors, along with degraded human performance, can be better avoided through implementing Human Factors considerations during the early stages of the system design process.⁴

3.6 The cost associated with lost lives and injuries due to the lack of proper Human Factors consideration during design and certification of the technology cannot be overstated. Research has clearly shown that technology-produced problems will not be eliminated by more technology, especially in highly advanced systems where human operators are expected to bear full responsibility for their own as well as the automated systems' actions.

... Most of us choose to think of the human role in our sophisticated technological society as a minor part of the equation. We accept a walk-on part in the modern world and give the machines, the systems, the lead. Again and again, in the wake of catastrophe, we look for solutions that will correct "it" rather than "us." ... But no machine is more trustworthy than the humans who made it and operate it. So we are stuck. Stuck here in the high-risk world with our own low-tech species, like it or not. No mechanical system can ever be more perfect than the sum of its very Human Factors.⁵

3.7 Human-centred technology (automation), by integrating Human Factors considerations into the system design process, can resolve human error issues in highly advanced automated systems, thereby preempting future disasters and accidents.

2. For further discussion on benefits to be had from Human Factors investment at early stage, see Harold E. Price, "Conceptual System Design and the Human Role", in *MANPRINT*. Van Nostrand Reinhold, New York, 1990.

3. Reason, J., *Human Error*. Cambridge University, United Kingdom, 1990.

4. ICAO Human Factors Digest No. 10 — *Human Factors, Management and Organization* (Circular 247).

5. Ellen Goodman, "The Boston Globe Newspaper Company/Washington Post Writers Group", 1987. Quoted in Harold E. Price, "Conceptual System Design and the Human Role", in *MANPRINT*, Harold R. Booher (ed.). Van Nostrand Reinhold, New York, 1990.

Human-centred technology (automation) reduces costs

3.8 Costs associated with the introduction of new technology have mostly been determined during the concept exploration phase of system development. To keep costs down, Human Factors considerations are often left out of initial design considerations (in the hope that personnel training will make up for design deficiencies). The result has been the multiplication of downstream costs (training, operation and maintenance) far beyond the initial savings. Changes to ensure that trained personnel can operate the system, after system design has been set, are more difficult and costly.⁶

3.9 There is a front-end cost associated with human-centred technology (automation) in the conceptual stages, but, compared to the everyday operating costs induced by inadequate design, it is negligible.

There is an “iron law” that should never be ignored. To consider Human Factors properly at the design and certification stage is costly, but the cost is paid only once. If the operator must compensate for incorrect design in his training program, the price must be paid every day. And what is worse, we can never be sure that when the chips are down, the correct response will be made.⁷

3.10 In addition to the unnecessary costs associated with obvious breakdowns in the machine and human interface, there is an even greater cost associated with everyday degradation in overall system performance. Because of inadequate consideration of the human role during conceptual design, systems frequently do not perform as expected.

3.11 Systems that employ human-centred technology and integrate human capabilities, limitations and expectations into system design are easier to learn and operate, thus considerably reducing the ultimate investment in training and operating costs. Human-centred automation design is a one-time investment — it becomes a permanent part of the system at large. Conversely, investment in personnel, manpower and training are recurring costs. Thus, Human Factors considerations into early system design is one sure way to avoid later costs.

3.12 Generally speaking, lack of Human Factors considerations in the design and operation of systems will invariably cause inefficiencies, problems, accidents and the loss of property and lives.

3.13 The ability of humans to recognize and define the expected, to cope with the unexpected, to innovate and to reason by analogy when previous experience does not cover a new problem is what has made the aviation system robust, for there are still many circumstances that are neither directly controllable nor fully predictable. Each of these uniquely human attributes in addition to sub-cultural considerations is a compelling reason to retain the human in a central position in the design of appropriate automation for the advanced aviation system. Appropriate automation is automation which is suited to the user population and the environment in which it is used. As such it should be bound within certain principles: *the principles of human-centred automation*.⁸

6. For further discussion on this topic, see Harold E. Price, “Conceptual System Design and the Human Role”, in *MANPRINT*. Van Nostrand Reinhold, New York, 1990.

7. Wiener, E.L., “Management of Human Error by Design”, Human Error Avoidance Techniques Conference Proceedings. Society of Automotive Engineers, Inc., 1988.

8. Billings, C.E., “Human-Centered Aircraft Automation: A Concept and Guidelines”. NASA Technical Memorandum 103885, 1991.

Chapter 4

PRINCIPLES OF HUMAN-CENTRED AUTOMATION

4.1 It has already been advanced that modern day automation is capable of performing nearly all of the functions envisaged in the aviation system both in the aircraft and on the ground. We have also shown that the human should, mainly in the interest of safety and economic advantages, remain the central focus in its design. Questions regarding future automation principles will, of necessity, have to relate to the respective roles of the humans and machines. It is accepted that humans will retain responsibility for system safety. For this simple, but most important, reason they will also have to remain in full command of the automated systems for which they are responsible.

4.2 A study conducted by one State outlined high-level operating guidelines when a highly automated ATC system (AERA 2 — Automatic En-Route Air Traffic Control) becomes operational in 1999. It states that:

Responsibility for safe operation of aircraft remains with the pilot in command.

Responsibility for separation between controlled aircraft remains with the controller.

Since detecting conflicts for aircraft on random routes is more difficult than if the traffic were structured on airways, the controller will have to rely on the (automated) systems to detect problems and to provide resolutions that solve the problem.

Alerts may be given in situations where later information reveals that separation standards would not be violated... This is due to uncertainty in trajectory estimation... Therefore, alerts must be given when there is possibility that separation may be violated, and the controller must consider all alerts valid.

The Executive Summary states,

Machine-generated resolutions offered to a controller that are free of automation-identified objections are assumed feasible and implementable as presented.

The controller will use automation to the maximum extent possible.¹

4.3 It is far from clear whether air traffic controllers in the AERA system will be able to exercise more than limited authority, but it is quite clear that they will continue to be *fully responsible* for the safety of air traffic. How long can it be before advances in air-ground automation place other human operators in the aviation system (pilots, dispatchers, maintenance technicians, etc.) in a similar position? And how is it that human operators will be held accountable for the safe operation of the aviation system when they do not have complete control of the operation they are supposed to be responsible for? As long as human operators are

1. MITRE Corporation, an engineering firm that conducts systems analysis and provides engineering technical support and guidance to the Federal Aviation Administration (FAA). In Charles E. Billings, "Human-Centered Aircraft Automation: A Concept and Guidelines". National Aeronautics and Space Administration (NASA) Technical Memorandum 103885, 1991.

required to be fully responsible for the safe operation of the system, tools (automation or otherwise) designed to assist them undertake their responsibility should be designed with the human operator in mind. To effect this, regulators, designers, operators and users should employ guidelines, or principles, for the design and operation of automated systems envisaged to be employed in the system and assist the human operators to successfully undertake their responsibilities.

PRINCIPLES OF HUMAN-CENTRED AUTOMATION
<p>THE HUMAN BEARS THE ULTIMATE RESPONSIBILITY FOR THE SAFETY OF THE AVIATION SYSTEM.</p> <p>THEREFORE:</p> <ul style="list-style-type: none"> • THE HUMAN MUST BE IN COMMAND. • TO COMMAND EFFECTIVELY, THE HUMAN MUST BE INVOLVED. • TO BE INVOLVED, THE HUMAN MUST BE INFORMED. • FUNCTIONS MUST BE AUTOMATED ONLY IF THERE IS A GOOD REASON FOR DOING SO. • THE HUMAN MUST BE ABLE TO MONITOR THE AUTOMATED SYSTEM. • AUTOMATED SYSTEMS MUST, THEREFORE, BE PREDICTABLE. • AUTOMATED SYSTEMS MUST BE ABLE TO MONITOR THE HUMAN OPERATOR. • EACH ELEMENT OF THE SYSTEM MUST HAVE KNOWLEDGE OF THE OTHERS' INTENT. • AUTOMATION MUST BE DESIGNED TO BE SIMPLE TO LEARN AND OPERATE.

4.4 The application of these principles is central in the preliminary and final design processes of automated systems in highly advanced technologies. The core of the matter is that *automation is employed to assist human operators to undertake their responsibilities in the most efficient, effective, economical and safe manner*. It should never be the other way around. Questions raised in previous chapters on how much authority automation should have, how it will interact with the human operator, and what role should be reserved for the human can only be satisfied by the application of a set of principles during the design, development and operation of an automation system. Antoine de Sainte-Exupéry's observation that "the machine does not isolate man from the great problems of nature but plunges him more deeply into them" holds true now even more than it did during the late 1930s, when it was voiced.

4.5 Over time, progress in aviation safety has been hindered by piecemeal approaches. Pilots, controllers, designers, engineers, researchers, trainers and others in the aviation safety community have advocated solutions to safety deficiencies which are undoubtedly biased by their professional backgrounds. Such approaches have neglected to look into the big picture of aviation system safety, and have thus produced dedicated solutions to observed deficiencies and conveyed the notion that different activities within aviation take place in isolation. As mentioned elsewhere in this document, the principles of human-centred automation require that the industry embrace a system approach to the design of automation systems. Advantages of incorporating Human Factors considerations early in system design cannot be overstated.

- **The human bears the ultimate responsibility for the safety of the aviation system.** History has shown us over and over again that in a complex system, no matter how automated, the human has the last vote in deciding a critical issue and the human is the last line of defence in case of system breakdown. The importance of people in a technological society is further reflected in the concept of *pivotal people*. Pfeiffer (1989) emphasizes the irreplaceability of pivotal people in stressful environments like flight operations, air traffic control, and power

utility grid control.² So when discussing automation in aviation system, it should always be borne in mind that if people are to function efficiently, effectively and safely, Human Factors considerations must be integrated in the system starting at the conceptual stage and not appended later on as part of a default decision.

- **The human operator must be in command.** For humans to assume ultimate responsibility for the safety of the system, they should be conferred with essentially unlimited authority to permit them to fulfil this ultimate responsibility. It has been unequivocally stated that even when the automated system is in full operation, “responsibility for safe operation of an aircraft remains with the pilot-in-command,” and “responsibility for separation between controlled aircraft remains with the controller.” If they are to retain the *responsibility* for safe operation or separation of aircraft, pilots and controllers must retain the *authority* to command and control those operations. It is the fundamental tenet of the concept of human-centred automation that aviation systems (aircraft and ATC) automation exists to assist human operators (pilots and controllers) in carrying out their responsibilities as stated above. If this principle is not strictly observed, and if decisions are made by automated systems instead of by human operators, complicated and unavoidable liability issues may arise. This will obviously lead into consideration of the human operator’s share of liability, which in turn will adversely affect human performance. Thus, a question of liability becomes a Human Factors issue by default. Human operators should never be held liable for failures or erroneous decisions unless they have full control and command of the system. The reasons are very simple — like any other machine, automation is subject to failure. Further, digital devices fail unpredictably, and produce unpredictable manifestations of failures. The human’s responsibilities include detecting such failures, correcting their manifestations, and continuing the operation safely until the automated systems can resume their normal functions. Since automation cannot be made failure-proof, automation must not be designed in such a way that it can subvert the exercise of the human operator’s responsibilities.
- **To command effectively, the human operator must be involved.** To assume the ultimate responsibility and remain in command of the situation, human operators must be involved in the operation. They must have an active role, whether that role is to actively control the system or to manage the human or machine resources to which control has been delegated. If humans are not actively involved, it is likely that they will be less efficient in reacting to critical system situations. Human-centred aviation system automation must be designed and operated in such a way that it does not permit the human operator to become too remote from operational details, by requiring of that operator meaningful and relevant tasks throughout the operation.
- **To be involved, the human must be informed.** Without information about the conduct of the operation, involvement becomes unpredictable and decisions, if they are made, become random. To maintain meaningful involvement, the human operator must have continuing flow of essential information concerning the state and progress of the system controlled and the automation that is controlling it. The information must be consistent with the responsibilities of the human operator; it must include all the data necessary to support the human operator’s involvement in the system. The human operators must be prominently informed at the level required to fulfil their responsibilities. The human operators must have enough information to be able to maintain state and situation awareness of the system. However, care must be taken not to overload them with more information than is necessary.

2. Pfeiffer, J., “The Secret of Life at the Limits: Cogs Become Big Wheels”, in *Smithsonian*, Vol. 27, No. 4, 1989.

- **Functions must be automated only if there is a good reason for doing so.** There is a growing temptation to incorporate some new technology showpiece in a design just because it can be done rather than because it is necessary. In other words, designs may be driven by technological feasibility rather than the needs of the users who must operate and maintain the products of these designs. Automation of functions for no other reason except that it is technologically possible may result in the user's inability to effectively employ it for the benefit of the whole system. The question here should be "not whether a function can be automated, but whether it needs to be automated, taking into consideration the various Human Factors questions that may arise".³
- **The human must be able to monitor the automated system.** The ability to monitor the automated systems is necessary both to permit the human operator to remain on top of the situation, and also because automated systems are fallible. The human can be an effective monitor only if cognitive support is provided at the control station. Cognitive support refers to the human need for information to be ready for actions or decisions that may be required. In automated aviation systems, one essential information element is information concerning the automation. The human operator must be able, from information available, to determine that automation performance is, and in all likelihood will continue to be, appropriate to the desired system situation. In most aviation systems to date, the human operator is informed only if there is a discrepancy between or among the units responsible for a particular function, or a failure of those units sufficient to disrupt or disable the performance of the function. In those cases the operator is usually instructed to take over control of that function. To be able to do so without delay, it is necessary that the human operator be provided with information concerning the operations to date if these are not evident from the behaviour of the system controlled.
- **Automated systems must be predictable.** The human operator must be able to evaluate the performance of automated systems against an internal model formed through knowledge of the normal behaviour of the systems. Only if the systems normally behave in a predictable fashion can the human operator rapidly detect departures from normal behaviour and thus recognize failures in the automated systems. In so stating, it is important that not only the nominal behaviour, but also the range of allowable behaviour be known. All unpredicted system behaviour must be treated as abnormal behaviour. To recognize this behaviour, the human operator must know exactly what to expect of the automation when it is performing correctly.
- **Automated systems must also be able to monitor the human operator.** Humans, of course, are not infallible either, and their failures may likewise be unpredictable. Because human operators are prone to errors, it is necessary that error detection, diagnosis and correction be integral parts of any automated aviation system. For this reason, it is necessary that human as well as machine performance be continuously monitored. Monitoring automation capable of questioning certain classes of operator's actions that can potentially compromise safety must be designed into the system.
- **Each element of the system must have knowledge of the others' intent.** In highly automated operations, one way to keep the human operator actively involved is to provide him or her with information concerning the *intent* of the automated system. That is, given the current decisions made or about to be made by the automated systems, what will the situation look like in the future. Essentially, the system should not only identify a potential problem but also

3. Wiener, E.L. and R.E. Curry, *Ergonomics*. 1980.

suggest alternative solutions and show the implications of the action taken. Cross-monitoring can only be effective if the monitor understands what the operator of the monitored system is trying to accomplish. To obtain the benefit of effective monitoring, the intentions of the human operator or the automated systems must be known. The communication of intent makes it possible for all involved parties to work co-operatively to solve any problem that may arise. For example, many air traffic control problems occur simply because pilots do not understand what the controller is trying to accomplish, and the converse is also true. The automation of the ATC system cannot monitor human performance effectively unless it understands the operator's intent, and this is most important when the operation departs from normality.

- **Automation must be designed to be simple to learn and operate.** One of the major objectives of this digest is to consider *how much automation is necessary, and why*. If systems are sufficiently simple (and this should always be a design goal) automation may not be needed. If tasks cannot be simplified, or are so time-critical that humans may not be able to perform them effectively, automation may be the solution. Even then, simpler automation will permit simpler interfaces and better human understanding of the automated systems. Systems automation to date has not always been designed to be operated under difficult conditions in an unfavourable environment by overworked and distracted human operators of below-average ability. Yet these are precisely the conditions where the assistance of the automation system may be most needed. Simplicity, clarity and intuitiveness must be among the cornerstones of automation design, for they will make it a better and effective tool. Though training, strictly speaking, is not the province of the designers, training must be considered during the design of the components of the CNS/ATM systems and should reflect that design in practice. Good Human Factors Engineering (HFE) design is marked by an absence of problems in the use of a system by humans and its effects are thus invisible in the final operational system. Its contributions become an integral part of each component or subsystem, and cannot be readily isolated from over-all system functioning or credit to the HFE inputs.⁴

4.6 In establishing the basic guidelines for the principles of human-centred automation, it should be noted that no attempt has been made to cover the engineering aspects of Human Factors. The attempt is only to construct a philosophy of *human-centred automation*. By so doing, it is hoped to foster a dialogue which will further the over-all goal of promoting a safe, orderly and economical aviation environment, integrating the best of both the human and the machine.

4.7 The principles of human-centred automation are intended to serve as a template so that every time automation is designed and introduced it can be filtered through the template rather than justified and defended anew.

4. Lane, N.E., "Evaluating the Cost Effectiveness of Human Factors Engineering". Orlando, Florida, Essex Corporation, 1987. Quoted in Harold E. Price, "Conceptual System Design and the Human Role", in *MANPRINT*. Van Nostrand Reinhold, New York, 1990.

Chapter 5

QUALITIES OF HUMAN-CENTRED AUTOMATION

5.1 Human error has been identified as the major causal factor in most aviation accidents. The most widely held perception, by people in all walks of life, is that the error causing human in those accidents is the “front-line operator”, simply stated as the pilot, air traffic controller, aircraft maintenance technician, etc. This perception, fuelled by the media and widely accepted by the public, has caused a lot of anxiety because it conceals the fact that the evolution of modern technology has made it practically impossible for one individual — the front-line operator — to cause an accident *all alone*. In those accidents where operator error has initially been identified as the causal factor, researchers were able to prove that the operator has only triggered a chain of latent failures, long embedded in the system, waiting undetected, or ignored for one reason or another. A line of defence is built into modern-day technology making it practically impossible for a single action to cause an unprecedented accident unless, the system has already been weakened by the elimination of those defences. It has been proved that design deficiencies, organizational and managerial shortcomings and many other latent failures were the root causes of many accidents attributed to the front-line operators, who in most cases do not survive the accidents to defend their actions.¹

5.2 Other accidents, also attributed to front-line operators, were found to have been caused as a result of the interaction of humans with automated systems (a mismatch of the human and machine elements of the system). Automation systems are made by humans. As such they can also harbour unplanned-for errors from as early as their conception. The belief that better training will make up for unthought-of deficiencies in the design and development stage has proved to be fallible. More gadgets and the introduction of more complex technology has only succeeded to make the machines inoperable because Human Factors considerations were not included in the basic concept. Human Factors researchers and specialists, accident investigators and analysts, human behaviour specialists and experts studying human-machine interactions agree that making automation human-centred can solve most human error associated problems. More importantly, they believe that automation can be designed and used to make the system, as a whole, more resistant to and tolerant of human errors in design, implementation, and operation of the systems. This implies that if automation is to be an effective and valued component of the aviation system, it should also possess several qualities or characteristics. By defining the attributes of human-centred automation, it is hoped that the system is made inherently and distinctively useful to the human operator who, after all, is burdened with full responsibility for its safety — human and non-human. In defining the attributes an automation system should possess, the intent once more is to promote dialogue on the subject, thus furthering the orderly and safe operation of the entire air transportation system.

5.3 In discussing the attributes of human-centred automation, it should be clear that they are not mutually exclusive. An automated system that possesses some, or even many, of these qualities may still not be fully efficient if they are considered in isolation during design, for several are interrelated. As in any engineering enterprise, it is necessary that the right compromise among the attributes be sought. To be sure that an effective compromise has been reached, the total system must be evaluated in actual or under a simulated operation by a variety of human operators of differing degrees of skill and experience. Such testing could be time-consuming and expensive and might often be conducted late in the development of the system;

1. Reason, J., *Human Error*. Cambridge University Press, United Kingdom, 1990.

nevertheless, it is the only way to prove the safety and effectiveness of the automated concept. Thus, the first guideline in attributes of human-centred automation might simply be that *human-centred automation should possess these qualities in proper measure*.

5.4 Many of these attributes are to some extent bipolar, though not truly opposites,² and increasing the attention on certain qualities may require de-emphasizing others. In the manner suggested, human-centred automation must be:

Accountable	<----->	Subordinate
Predictable	<----->	Adaptable
Comprehensible	<----->	Flexible
Dependable	<----->	Informative
Error-resistant	<----->	Error tolerant

- Human-centred automation must be accountable.** Automation must inform the human operator of its actions and be able to explain them on request. The human in command must be able to request and receive a justification for decisions taken by the automated system. This is a particular problem in aviation, as there may not be time for the human operator to evaluate several decisions (terrain avoidance, collision avoidance, etc.). Where possible, automation must anticipate the human operator's request and provide advance information (as TCAS intends to do by providing traffic advisories prior to requiring action to avoid an imminent hazard) or its rules of operation in a particular annunciated circumstance thoroughly understood by the human operator. It is particularly important that explanations provided by automation be cast in terms that make sense to the human operator; the level of abstraction of such explanations must be appropriate to the human operator's need for the explanation. In this context "accountable" means subject to giving a justifying analysis or explanation. The bipolar attribute of accountability is subordination. Great care must be taken to ensure that this cannot ever become insubordination.
- Human-centred automation must be subordinate.** Except in pre-defined situations, automation should never assume command and in those situations, it must be able to be countermanded easily. Automation, while an important tool, must remain subordinate to the human operator. There are situations in which it is accepted that automation should perform tasks autonomously, and more such tasks are expected to be implemented in the CNS/ATM system. As automation becomes more self-sufficient, capable and complex, it will be increasingly difficult for the human operators to remain aware of all actions being taken autonomously and thus increasingly difficult for them to be aware of exactly what the automation is doing and why. Such a situation will tend to compromise the command authority and responsibility of the human operators; more importantly, it may lead them to a position of extreme distrust of the automation system, which could compromise the integrity of the entire human-machine system. It is important to make questions such as "What is it doing?" and "Why is it doing that?" unnecessary.
- Human-centred automation must be predictable.** Occurrences in which automation did not appear to behave predictably have, in the past, led to major repercussions due in large part to human operators' inherent distrust of things over which they do not have control. Here again, the level of abstraction at which automation is explained, or at which it provides

2. See Charles E. Billings, "Human-Centered Aircraft Automation: A Concept and Guidelines". National Aeronautics and Space Administration (NASA) Technical Memorandum 103885, 1991.

explanation, is critical to the establishment and maintenance of trust in it. The third question most often asked by human operators of automation is “What’s it going to do next?”. This question, like the two above, should also be made unnecessary. As automation becomes more adaptive and intelligent, it will acquire a wider repertoire of behaviours under a wider variety of circumstances. This will make its behaviour more difficult for human operators to understand and predict, even though it may be operating in accordance with its design specifications. It will also be more difficult for human operators to detect when it is not operating properly. Advanced automation must be designed both to be, and to appear to be, predictable to its human operators, and the difference between failure and normal behaviour must be immediately apparent to the human operator.

- **Human-centred automation must be adaptable.** Automation should be configured within a wide range of operator preferences and needs. Adaptability and predictability are, in a sense, opposites, as highly adaptive behaviour is liable to be difficult to predict. As automation becomes more adaptive and intelligent, it will acquire a wider repertoire of behaviours under a wider variety of circumstances. This will make its behaviour more difficult for the human operator to understand and predict, even though it may be operating in accordance with its design specifications. It will also be more difficult for the human operator to detect when it is not operating normally. This suggests the necessity for constraints on the adaptability of automation to permit the human to monitor the automation and detect either shortcomings or failures in order to compensate for them. “Adaptable”, as used here, means capable of being modified according to changing circumstances. This characteristic is incorporated in aircraft automation: pilots need, and are provided with, a range of options for control and management of their aircraft. Similar options should also be available in CNS/ATM system automation. The range of options is necessary to enable the human operators to manage their workload (taking into account differing levels of proficiency) and compensate for fatigue and distractions. In this regard, automation truly acts as an additional member of the control and management team, assisting with or taking over entirely certain functions when instructed to do so. Adaptability increases apparent complexity and is shown here contrasted with predictability, to emphasize that extremely adaptable automation may be relatively unpredictable in certain circumstances. If such a system is not predictable, or if it does not provide the human operator with sufficient indication of its intentions, its apparently capricious behaviour will rapidly erode the trust that the human wishes to place in it. It is good to remember that one of the first principles of human-centred automation states that automation *must* be predictable, if the human is to remain in command.
- **Human-centred automation must be comprehensible.** Technological progress is often equated with increased complexity. Many critical automation functions are now extremely complex, with several layers of redundancy to insure that they are fault-tolerant. It has been noted that training for advanced automated systems is time-consuming and expensive, and that much of the extra time is spent learning about the automation. Simpler models that permit reversion in case of failures should be devised. This will result in training benefits. While automation can be used to make complex functions appear simpler to the human operator, the consequences of failure modes can appear to be highly unpredictable to that human operator unless the modes are very thoroughly considered in the design phase. Simplicity has not been included as a necessary attribute for human-centred automation, but it could well have been. It is vital that systems either be simple enough to be understood by human operators, or that a simplified construct be available to and usable by them. If a system cannot be made to appear reasonably simple to the human operator, the likelihood that it will be misunderstood and operated incorrectly increases significantly. CNS/ATM systems automation

designers and manufacturers should make a considerable effort to make their products simple enough to be comprehended by human operators of widely differing skill level.

- **Human-centred automation must be flexible.** An appropriate range of control and management options should be available. The term “flexible” is used here to characterize automation that can be adapted to a variety of environmental, operational and human variables. A wide range of automation options must be available to provide flexibility for a wide range of human operators with experience that varies from very little to a great deal and cognitive styles that vary as widely. Given the tendency to an inverse relationship between comprehensibility and flexibility, comprehensibility must not be sacrificed for flexibility, because the ability of the human operators to understand their automation is central to their ability to maintain command.
- **Human-centred automation must be dependable.** Automation should do, dependably, what it is ordered to do, it should never do what it is ordered not to do and it must never make the situation worse. Humans will not use, or will regard with suspicion, any automated system or function that does not behave reliably, or that appears to behave capriciously. This distrust can be so ingrained as to nullify the intended purpose of the designer. Dependability is of a particular importance with respect to alerting and warning systems. Mistrust of legitimate warnings by systems which were prone to false warnings (such as early models of GPWS) have in the past resulted in tragic consequences. In fact, it may be wiser to omit a function entirely, even a strongly desired function, rather than to provide or enable it before it can be certified as reliable.
- **Human-centred automation must be informative.** Information is critical both for involvement in the task and for maintaining command over it. If a system were perfectly dependable in operation, there might be no need to inform the human operator of its operation. Perfection is impossible to achieve, however, and the information provided must be as nearly foolproof as possible, bearing in mind that each increase in information quantity makes it more likely that the information may be missed, or even incorrect. One of the first principles of human-centred automation is that “in order to be involved the human *must* be informed.” But, how much information is enough? How much is too much? Human operators want all the information they can get, but they cannot assimilate too much, and what they will leave out is unpredictable. It is desirable to declutter and simplify displays and format changes; in short, to provide for *active* as opposed to *passive* information management, to assist the human operator in assigning priorities to ensure that the most important things are attended to first. Problems may, once again, arise because of automation itself, or simply because the interfaces between the automation and the human are not optimal. The form of information will often determine whether it can be attended to or not and it should be considered during the development of any CNS/ATM information system.
- **Human-centred automation must be error-resistant.** Automation must keep human operators from committing errors wherever that is possible. Ideally, ATM automation system should prevent the occurrence of all errors, both its own and those of the human operators. This may be unrealistic, but a system can and must be designed to be as error-resistant as possible. Resistance to error in automation itself may involve internal testing to determine that the system is operating within its design guidelines. Resistance to human error may involve comparison of human actions with a template of permitted actions, or may be based on clear, uncomplicated displays and simple, intuitive procedures to minimize the likelihood of errors. Automation of unavoidably complex procedures is necessary and entirely appropriate,

provided the human is kept in the loop so he or she understands what is going on. The system must be able to be operated by the human if the automation fails, and it must provide an unambiguous indication that it is functioning properly. It is also essential to provide means by which human operators can detect the fact that human or automation error has occurred. Such warnings must be provided with enough time to permit human operators to isolate the error, and a means must be provided by which to correct the error once it is found. Where this is impossible, the consequences of an action must be queried before the action itself is allowed to proceed.

- **Human-centred automation must be error-tolerant.** Some errors will occur, even in a highly error-resistant system; therefore, automation must be able to detect and mitigate the effect of these errors. Since error-resistance is relative rather than absolute, there needs to be a “layered defence” against human errors. Besides building systems to resist errors as much as possible, it is necessary and highly desirable to make systems tolerant of error. In this sense, “tolerance” means the act of allowing something; it covers the entire panoply of means that can be used to ensure that when an error is committed, it will not be allowed to jeopardize safety. The aviation system is already highly tolerant of errors, largely through monitoring by other team members. But certain errors possible with automated equipment, such as data entry errors, may only become obvious long after they are committed. New monitoring software, displays and devices may be required to trap the more covert errors. In such cases, checks of actions against reasonableness criteria may be appropriate. Given that it is impossible either to prevent or trap all possible human errors, previous aviation occurrences and especially incident data can be extremely useful in pointing out the kinds of errors that occur with some frequency.

5.5 The attributes of a human-centred automation suggested above are not mutually exclusive; there is overlap among them. The first principles suggest a rough prioritization where compromise is necessary. It is stated that if humans are to be in command, they must be informed. *Accountability* is an important facet of informing the human operator, as well as an important means by which the operator can monitor the functioning of the automation. *Comprehensibility* is another critical trait if the human is to remain informed; he or she must be able to understand what the automation is doing. Each of these traits is an aspect of *informativeness*. At all times, the human operator must be informed effectively of at least that minimum of information, and informed in such a way that there is a very high probability that the information will be assimilated. In those cases where an automated system acts in an unpredictable manner, an explanation should be readily available if it is not already known or fairly obvious.

5.6 With the inevitable exceptions, regulators and the public-at-large agree that humans bear the ultimate responsibility for the safety of the civil aviation system. This suggests that humans must remain in full command of the whole system. However, despite this assertion, it is thought that the independence of automation may tend to bypass the human operator as more and more of the ground elements of the air transportation system are automated. Automation that bypasses the human operators will of necessity diminish their involvement in the aviation system and their ability to command it, which in turn will diminish their ability to recover from failures or compensate for inadequacies in the automated subsystems. Automation designers should conclusively prove that such inadequacies will not exist or such failures will not occur before the aviation community can consider automation systems which can bypass the human operator. It is important that a balance be struck; where compromises are necessary, they must err on the side of keeping the human operator in the loop so that he or she will be there when needed.

5.7 Despite spectacular technological advances in automation, the effectiveness of automated and computerized systems remains inextricably linked to the performance capabilities of human operators. ATM

automation will force drastic changes in the role of the human operator; it may also cause major changes in the process by which air traffic controllers and pilots work together to accomplish the mission in a most safe manner. If an automated ATM system inhibits the ability of controllers and pilots to work co-operatively to resolve problems, it will severely limit the flexibility of the system, and the loss of that flexibility could undo much of the benefit expected from a more automated system. In this context, advanced automated or computerized systems in the CNS/ATM system should be designed to help humans accomplish new and difficult tasks and safely challenge the needs and requirements of tomorrow. Over time, technology intended to increase safety margins has been used to increase throughput, leaving safety margins relatively unchanged. If humans are to remain fully responsible for system safety, automation should *not* be used to increase system throughput beyond the limits of human capability to operate manually in the event of system automation failure. In developing the various components of the CNS/ATM system, designers and manufacturers as well as regulators should remember that the most important facet of the whole system is the human who operates, controls or manages the whole system in pursuit of human and social objectives.

5.8 Generally speaking, automation evolution to date has been largely technology-driven. However, designers of new aircraft and other aviation systems in recent years have made a determined attempt to help humans do what they may not do well in the press of day-to-day operations. In doing so they have helped to eliminate some causes of human error, while enabling others directly associated with the new technology.

5.9 The CNS/ATM system is expected to permit more flexible and efficient use of airspace and enhance traffic safety. The air traffic management enhancements envisaged include:

- improved handling and transfer of information between operators, aircraft and ATS units;
- extended surveillance (automatic dependent surveillance (ADS), etc.); and
- advanced ground-based data processing systems, including systems to display ADS-derived data and aircraft-originated data to the controller allowing for, among other things, improvement in conflict detection and resolution, automated generation and transmission of conflict-free clearances, and rapid adaptation to changing traffic conditions.

5.10 The development of the basic aims of the CNS/ATM system including that of future advanced aviation systems, together with improved planning, is expected to enhance safety and allow more dynamic use of airspace and air traffic management. In doing so, it is obvious that more automation will be required and utilized. The challenge is to develop a system based on the principles of human-centred automation which takes into account human capabilities and limitations and in summary suggests that:

- **Humans must remain in command of flight and air traffic operations.**
Automation can assist by providing a range of management options.
- **Human operators must remain involved.**
Automation can assist by providing better and more timely information.
- **Human operators must be better informed.**
Automation can assist by providing explanations of its actions and intentions.

- **Human operators must do a better job of anticipating problems.**
Automation can assist by monitoring trends, making predictions and providing decision support.
- **Human operators must understand the automation provided to them.**
Designers can assist by providing simpler, more intuitive automation.
- **Human operators must manage all of their resources effectively.**
Properly designed and used, automation can be their most useful resource.

5.11 All concepts presented in this digest go beyond theory; they can be put to very practical use. The goal is to influence the design of human-machine systems so that human capabilities and limitations are considered from the early stages of the design process, and are accounted for in the final design. A design that considers such issues will result in a system that enhances safety, productivity and job satisfaction. The Human Factors profession can provide system designers who possess all the necessary expertise and know-how to incorporate these principles during design.

5.12 ICAO will endeavour to procure specific examples on how each principle can be incorporated into an automated air traffic management system. The information will then be made available to States as guidance in applying the information in this digest.

Appendix 1

STATEMENT OF ICAO POLICY ON CNS/ATM SYSTEMS IMPLEMENTATION AND OPERATION

Approved by Council on 9 March 1994

In continuing to fulfil its mandate under Article 44 of the Convention on International Civil Aviation by, *inter alia*, developing the principles and techniques of international air navigation and fostering the planning and development of international air transport so as to ensure the safe and orderly growth of international civil aviation throughout the world, the International Civil Aviation Organization (ICAO), recognizing the limitations of the present terrestrial-based system, developed the ICAO communications, navigation and surveillance/air traffic management (CNS/ATM) systems concept, utilizing satellite technology. ICAO considers an early introduction of the new systems to be in the interest of healthy growth of international civil aviation. The implementation and operation of the new CNS/ATM systems shall adhere to the following precepts.

1. Universal accessibility

The principle of universal accessibility without discrimination shall govern the provision of all air navigation services provided by way of the CNS/ATM systems.

2. Sovereignty, authority and responsibility of Contracting States

Implementation and operation of CNS/ATM systems which States have undertaken to provide in accordance with Article 28 of the Convention shall neither infringe nor impose restrictions upon States' sovereignty, authority or responsibility in the control of air navigation and the promulgation and enforcement of safety regulations. States' authority shall be preserved in the co-ordination and control of communications and in the augmentation, as necessary, of satellite navigation services.

3. Responsibility and role of ICAO

In accordance with Article 37 of the Convention, ICAO shall continue to discharge the responsibility for the adoption and amendment of Standards, Recommended Practices and Procedures governing the CNS/ATM systems. In order to secure the highest practicable degree of uniformity in all matters concerned with the safety, regularity and efficiency of air navigation, ICAO shall co-ordinate and monitor the implementation of the CNS/ATM systems on a global basis, in accordance with ICAO's regional air navigation plans and global co-ordinated CNS/ATM systems plan. In addition, ICAO shall facilitate the provision of assistance to States with regard to the technical, financial, managerial, legal and co-operative aspects of implementation. ICAO's role in the co-ordination and use of frequency spectrum in respect of communications and navigation in support of international civil aviation shall continue to be recognized.

4. Technical co-operation

In the interest of globally co-ordinated, harmonious implementation and early realization of benefits to States, users and providers, ICAO recognizes the need for technical co-operation in the implementation and efficient operation of CNS/ATM systems. Towards this end, ICAO shall play its central role in co-ordinating technical co-operation arrangements for CNS/ATM systems implementation. ICAO also invites States in a position to do so to provide assistance with respect to technical, financial, managerial, legal and co-operative aspects of implementation.

5. Institutional arrangements and implementation

The CNS/ATM systems shall, as far as practicable, make optimum use of existing organizational structure, modified if necessary, and shall be operated in accordance with existing institutional arrangements and legal regulations. In the implementation of CNS/ATM systems, advantage shall be taken, where appropriate, of rationalization, integration and harmonization of systems. Implementation should be sufficiently flexible to accommodate existing and future services in an evolutionary manner. It is recognized that a globally co-ordinated implementation, with full involvement of States, users and service providers through, *inter alia*, regional air navigation planning and implementation groups, is the key to the realization of full benefits from the CNS/ATM systems. The associated institutional arrangements shall not inhibit competition among service providers complying with relevant ICAO Standards, Recommended Practices and Procedures.

6. Global navigation satellite system

The global navigation satellite system (GNSS) should be implemented as an evolutionary progression from existing global navigation satellite systems, including the United States' global positioning system (GPS) and the Russian Federation's global orbiting navigation satellite system (GLONASS), towards an integrated GNSS over which Contracting States exercise a sufficient level of control on aspects related to its use by civil aviation. ICAO shall continue to explore, in consultation with Contracting States, airspace users and service providers, the feasibility of achieving a civil, internationally controlled GNSS.

7. Airspace organization and utilization

The airspace shall be organized so as to provide for efficiency of service. CNS/ATM systems shall be implemented so as to overcome the limitations of the current systems and to cater for evolving global air traffic demand and user requirements for efficiency and economy while maintaining or improving the existing levels of safety. While no changes to the current flight information region organization are required for implementation of the CNS/ATM systems, States may achieve further efficiency and economy through consolidation of facilities and services.

8. Continuity and quality of service

Continuous availability of service from the CNS/ATM systems, including effective arrangements to minimize the operational impact of unavoidable system malfunctions or failure and achieve expeditious service recovery, shall be assured. Quality of system service shall comply with ICAO Standards of system integrity and be accorded the required priority, security and protection from interference.

9. Cost recovery

In order to achieve a reasonable cost allocation between all users, any recovery of costs incurred in the provision of CNS/ATM services shall be in accordance with Article 15 of the Convention and shall be based on the principles set forth in the *Statements by the Council to Contracting States on Charges for Airports and Air Navigation Services* (Doc 9082), including the principle that it shall neither inhibit nor discourage the use of the satellite-based safety services.

Appendix 2

LIST OF RECOMMENDED READING

List of Recommended Reading

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— END —

ICAO TECHNICAL PUBLICATIONS

The following summary gives the status, and also describes in general terms the contents of the various series of technical publications issued by the International Civil Aviation Organization. It does not include specialized publications that do not fall specifically within one of the series, such as the Aeronautical Chart Catalogue or the Meteorological Tables for International Air Navigation.

International Standards and Recommended Practices are adopted by the Council in accordance with Articles 54, 37 and 90 of the Convention on International Civil Aviation and are designated, for convenience, as Annexes to the Convention. The uniform application by Contracting States of the specifications contained in the International Standards is recognized as necessary for the safety or regularity of international air navigation while the uniform application of the specifications in the Recommended Practices is regarded as desirable in the interest of safety, regularity or efficiency of international air navigation. Knowledge of any differences between the national regulations or practices of a State and those established by an International Standard is essential to the safety or regularity of international air navigation. In the event of non-compliance with an International Standard, a State has, in fact, an obligation, under Article 38 of the Convention, to notify the Council of any differences. Knowledge of differences from Recommended Practices may also be important for the safety of air navigation and, although the Convention does not impose any obligation with regard thereto, the Council has invited Contracting States to notify such differences in addition to those relating to International Standards.

Procedures for Air Navigation Services (PANS) are approved by the Council for world-wide application. They contain, for the most part, operating procedures

regarded as not yet having attained a sufficient degree of maturity for adoption as International Standards and Recommended Practices, as well as material of a more permanent character which is considered too detailed for incorporation in an Annex, or is susceptible to frequent amendment, for which the processes of the Convention would be too cumbersome.

Regional Supplementary Procedures (SUPPS) have a status similar to that of PANS in that they are approved by the Council, but only for application in the respective regions. They are prepared in consolidated form, since certain of the procedures apply to overlapping regions or are common to two or more regions.

The following publications are prepared by authority of the Secretary General in accordance with the principles and policies approved by the Council.

Technical Manuals provide guidance and information in amplification of the International Standards, Recommended Practices and PANS, the implementation of which they are designed to facilitate.

Air Navigation Plans detail requirements for facilities and services for international air navigation in the respective ICAO Air Navigation Regions. They are prepared on the authority of the Secretary General on the basis of recommendations of regional air navigation meetings and of the Council action thereon. The plans are amended periodically to reflect changes in requirements and in the status of implementation of the recommended facilities and services.

ICAO Circulars make available specialized information of interest to Contracting States. This includes studies on technical subjects.

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