Journal of Air Law and Commerce

Volume 42 | Issue 1 Article 10

1976

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INTRODUCTION

HUMAN ERROR is a fascinating though paradoxical subject. Each of us has had experience with it—we have all made errors—hence we are "expert," each in his own way. Still, the level of understanding of *why* accident-producing errors are made and more importantly, how better to control them is not very high. Only since the early 1960's has much serious research really been accomplished into the human error problem in aviation; albeit many investigators (*e.g.* McFarland at Harvard, Chapanis of Johns Hopkins University and Zeller of the USAF Directorate of Safety) had pioneered the subject earlier.[1]

As to the relationship between that popular kind of aviation human error, pilot error, and the design of airplanes, consider the following as an example that the problem has been around awhile. In July 1903, an otherwise unidentified intrepid aeronaut, Major L. S. Blackman, was experimenting with airfoils and gliders, especially their attendant stability problems. His "flight test" report, six months before the Kitty Hawk episode of the Wright Brothers, concluded by saying:

> [F]or the present and sometime to come, safety will depend chiefly on the skill of the aeronaut and the constructive strength of the machine.[2]

This was an accurate forecast. Of the first eleven Air Corps

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[1] Cornell, *Minimizing Human Errors*, SPACE/AERONAUTICS, May 1968.

[2] *Quote from* Blackman, AERONAUTICAL JOURNAL, 1903, *in* Brewer, *Point of Origin*, APPROACH, August 1964, at 2.

accidents, from September 1908 to February 1914, four were clearly and singularly pilot judgment problems; one combined judgment with a severe weather situation; four and probably a fifth were initially charged to pilot error but in retrospect suggest a design problem (misaligned thrust) which induced loss of control. Only one, the first one, was clearly a material-caused accident —the propellor broke.[3]

Interestingly enough, an analyst of these accidents indicated:

> It is evident that the machines in which the accidents occurred were not old, and the pilots were not novices . . . nearly every one of the accidents was due to the pilots and not the machines.[4]

The hours flown by these pilots ranged from twelve to eighty-six with corresponding numbers of flights ranging from fifty-two to 469!

We have come a long way in three quarters of an aviation century . . . or have we?

THEORIES OF HUMAN ERROR

In examining human error in general, several approaches to its categorization or interpretation can be identified. At the risk of oversimplification, in order to stay within practical confines for this article, and to use terminology for communication, not to demonstrate intellectual prowess, consider the following ways to think about human error.

1. *The Mistake Approach*

Certainly, this is the most traditional way to think of error which at least borders on blameworthiness, since error is intimately associated with our laws and other functional control precepts of our society. Do something "right" or as others expect or want you to do; else you have erred. Meister summarized this approach nicely when he categorized human error as:

(1) Performance of a required action incorrectly;
(2) Failure to perform the required action;
(3) Performance of a required action out of sequence; or

[3] Borden, *The First Eleven*, AEROSPACE SAFETY, May 1964, at 14.

[4] OFFICE OF THE CHIEF SIGNAL OFFICER, DEPARTMENT OF THE ARMY, MORTALITY IN AVIATION (memorandum) (Feb. 28, 1974).

(4) Performance of a non required action.[5]

Note the emphasis on "requirements" and the inference that judgments will be made as to the correctness of the actions. This presumes a "requirement" has been delineated clearly and that reasonable men can make something other than discriminatory value judgments. Of course, both of these presumptions are severely and routinely tested in the minds of those of us who have followed closely aviation accident investigations, resultant public hearings, tort litigation proceedings, etc.

2. *As A Task-overload*

This approach is perhaps the most modern way of examining human error and certainly the approach taken by the behaviorists. Usually, in aviation, this is described with reference to an illustration such as Figure 1. A flight is charted by phases along the abscissa, with the ordinate being the task loading required for a particular operation. A limit of pilot capacity is shown as at a theoretical upper limit running horizontally along the top of the illustration, but this limit can—and is—degraded by the realities of life, such as sickness, emotional variances, training deficiencies, etc. Similarly, the nominal task requirement can increase in the event of malfunctions of equipment or unique demands of the operational situation, whether resulting from emergencies or events implicit in the mission. The task overload theory simply presumes to examine the juxtaposition of tasks needed to be accomplished and the pilot's capability; and where they overlap, the error/accident is probable and thus something must be rectified—the tasks and/or the man.

3. *The Convenient Cubbyhole Concept*

This occurs when a classification of descriptive statements is developed which, at the moment, is logical in the mind of the system's creator. It gains acceptance with use and becomes improved to some degree with time. Major changes in the logic cannot be done, however, lest such changes inhibit analysis and communication of combined old and new data. Classic examples of this are found in manuals of accident code classifications such as

[5] Meister, *Methods of Predicting Human Reliability in Man-Machine Systems*, HUMAN FACTORS (Dec. 1964).

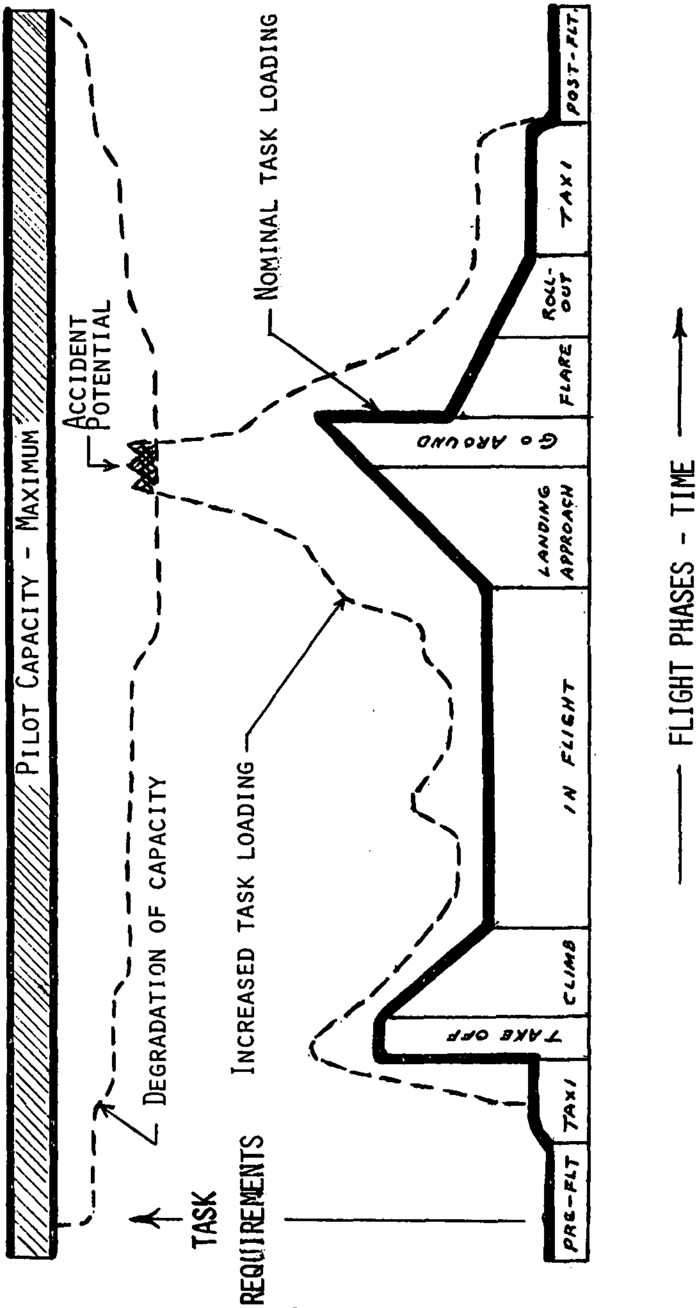

FIGURE 1
PILOT CAPABILITY AND WORKLOAD

that used by the National Transportation Safety Board (NTSB).[6] Phrases are contained therein like: "Continued VFR flight into adverse weather conditions," "Failed to extend landing gear," "Improper preflight preparation and/or planning," or "Misunderstanding of orders or instructions." The problem is that accident investigators are prone to stop their search for factual information short of *why* these situations develop, particularly if they are rushed, or if they do not understand human behavior sufficiently to ask adequate questions upstream of the obvious cause factor. Furthermore, if a behavioristic model were to be imposed to direct investigative search for more of the *why*, chances are the model would not be too compatible with the previously evolved logic.

4. *From the Accident Prevention Viewpoint*

Hopefully, this is the orientation that should be used in examination of errors made within the aviation system. It is exemplified by Pierson in an excellent, simple, two-page bulletin issued through the Flight Safety Foundation.[7] He suggested that pilot error should be examined on a "factor" basis and from the point of view of the type of corrective action that appears most practical. Accordingly, the major categories he chose were:

(1) Design-induced pilot factor;
(2) Operations-induced pilot factor;
(3) Environment-influenced pilot factor; and
(4) Innate pilot factor.

Respective sublistings pertaining to the above included items which could be designed out of the system (*e.g.*, instruments that cannot be seen properly because of their location); change in operational procedures (*e.g.*, air traffic control terminology); avoidance of certain environmental influences (*e.g.*, weather phenomena such as shallow fog or thunderstorms); and selection and control of human operators observing their inherent or acquired limitations (*e.g.*, medical and psychological conditions).

One of the landmark reports in this entire field, of course, was

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[6] BUREAU OF AVIATION SAFETY, NATIONAL TRANSPORTATION SAFETY BOARD, MANUAL OF CODE CLASSIFICATIONS, AIRCRAFT ACCIDENTS AND INCIDENTS (June, 1970).

[7] Pierson, *Taxonomy of Pilot Error (Factor)*, FLIGHT SAFETY FOUNDATIONS HUMAN FACTORS BULLETIN, (Jan./Feb. 1975).

the "Aircraft Design-Induced Pilot Error" (ADIPE) study conducted by the Bureau of Aviation Safety (BAS) then under the Civil Aeronautics Board (CAB).[8] Like Pierson, the authors of this study took an accident prevention approach and had, in fact, used a more encompassing definition of design-induced error, to wit:

> [T]he term 'Design-Induced Error' was considered as including all factors that may have influenced the action or non-action of the pilot and thus were related to the accident. Under this interpretation, factors that interfaced with action which might have prevented the accident, (including) the lack of data in flight manuals (and flight characteristics) requiring an unusual level of pilot competence are included among the factors inducing error.[9]

In other words, BAS went well beyond detail design deficiencies per se although emphasis was not lost on such things as "improper sensing of controls, inadequate identification of controls, inadequate indication and/or warning to the pilot and lack of standardization . . . ." A study sample of 3,732 cases was used that represented seventy-four percent of the total accidents occurring in 1964.

The findings of the ADIPE study were limited in 1967, as such an analysis would still be now, by the absence of an effective human-factors accident investigative protocol. Nevertheless, very significant conclusions were reached regarding stall-spin, groundloop, power plant failure, nose-over, hard landing, overshoot, undershoot, and retractable landing gear accidents.[10] Interestingly enough, a follow-up program to ADIPE was undertaken by the FAA which had actually funded the CAB/BAS effort. Updated data were obtained in October 1969 and September 1973, and statistical analyses similar to those in the original study were reportedly made; however, no reports have ever been published.

THE MAN-MACHINE SYSTEM

Activity in the pilot error field in recent years has been highlighted by a relatively informal NASA-industry working group comprised of representatives from United Airlines, Air Line Pilots'

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[8] BUREAU OF AVIATION SAFETY, CIVIL AERONAUTICS BOARD, AIRCRAFT DESIGN-INDUCED PILOT ERROR (Feb. 1967).

[9] *Id.*

[10] *Id.* at 131-35.

Association, Douglas Aircraft Co., and private consultants. With coordination effected by Dr. Charles E. Billings of the Man-Machine Integration Branch of the NASA Ames Research Center at Moffett Field, California, a preliminary working paper has been published.[11] The paper emphasizes the information processing aspect of the human error problem. That is, a behavioristic model is presented that can form the basis for more effective investigation and determination of human error variables including those which are design-induced. See Fig. 2. Indeed, this early working paper also contains outline material for interviewing that can aid significantly in human factors accident/incident investigations—the first step towards that missing investigative protocol noted earlier.[12] The effort by this working group was the predominant influence leading to the involvement of NASA in the FAA's "Aviation Safety Reporting System" scheduled to be implemented nationally during the spring of 1976.

Another way of examining the man-machine interface, which really is at the crux of the question of design-induced pilot error, was previously described by this author first in 1966 and again in 1974.[13] As noted in Figure 3, man and the machine interact in closed loop fashion. Man perceives, decides, and reacts (or responds) based on current stimuli with subsequent behavior also being a function of both memory (short and long term) and psycho-physiological capability. The resultant control functions thus affect the external stimuli and/or the data presented by the machine (*e.g.* instrument information), and the process starts over again. Or to place this in more literal terms, everything the man perceives, be it through a sensing process or through his memory, is a source of potential error. Whatever decision he makes, whether influenced by what he perceives or by his memory, is a source of

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[11] Barnhart, *et al*, *A Method for the Study of Human Factors in Aircraft Operations*, NASA TECHNICAL MEMORANDUM X-62, 472 (Sept. 1975).

[12] *See* text following note 10, *supra*.

[13] Address by C. O. Miller, "Safety Considerations and Human Reliability of the Experimental Test Pilot," *Human Factors Society* Annual Banquet, in Anaheim, California, Nov. 3, 1966; Address by C. O. Miller, "Legal Litigation Barriers to the Communication of Human Factors Safety Information," *Flight Safety Foundation* International Safety Seminar, in Williamsburg, Virginia, Nov. 1974 [hereinafter cited as *Address*].

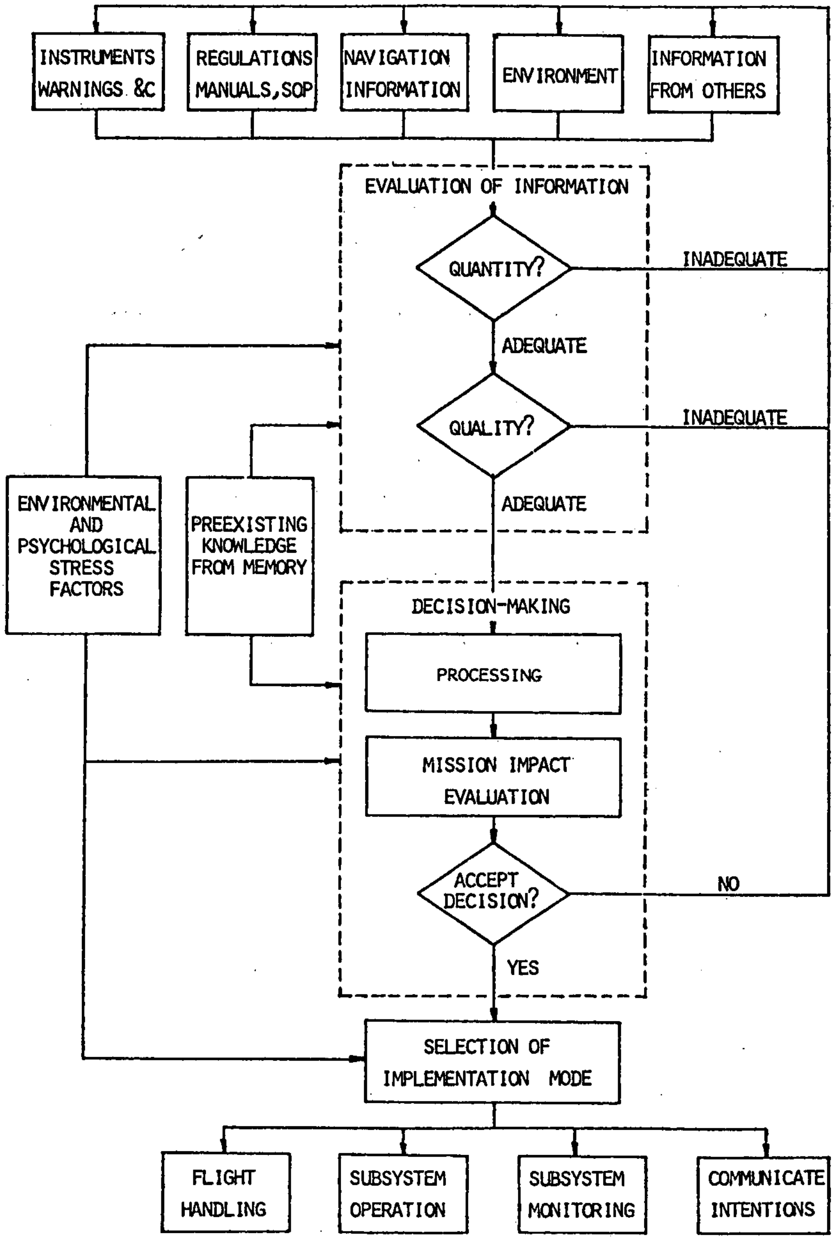

FIGURE 2
INFORMATION PROCESSING MODEL OF BEHAVIOR

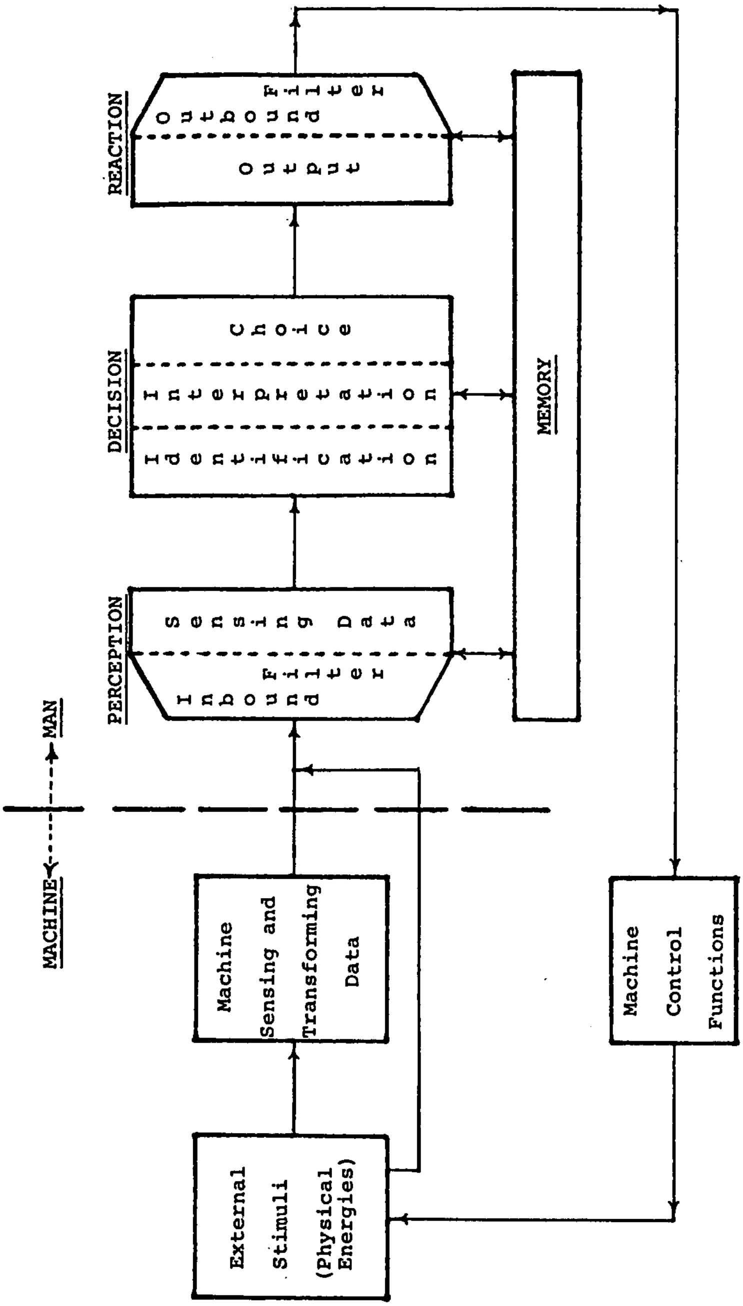

FIGURE 3
MAN-MACHINE BEHAVIORAL FLOW PATTERN

potential error. Each of his reactions, be it induced by a decision or something from his memory, is a source of potential error.

These potential errors occur in this very complicated process because the human being is the most complicated device ever conceived and is subject to certain capabilities and limitations. A person may not even realize he has these inbound and outbound "filters", allowing just certain types, quantities and qualities of "data"—to use a broad term—to be received. He can produce only certain types, quantities, and qualities of output. His identification, interpretation, and choice functions in particular are so highly dependent upon training and previous experience, as well as that elusive force, motivation, that errors in the decision process are commonplace. Fortunately, his corrective action capacity is phenomenal; that is, he can sense an unwanted deviation and revise his prior decisions and reactions before something serious develops. Hence, on balance, man is a very highly developed aid to system reliability and safety.

Of course, it is rare to be able to trace precisely these cause-effect mechanisms. This is particularly true if one is looking for legal certainty of the evidence. For as one legally oriented, but former pilot, NTSB Board Member was prone to say, everytime staff members tried to put something of human factors significance into one of the Board's blue cover reports: "How do you know what was going on inside the pilot's head?" He argued that insufficient hard data were available to "prove" the motivation and rationale for crew members' actions. He would never even accept opinions of qualified experts in psycho-social behavior, some of whom were on the Board's staff and others who were referenced or brought in for testimony. This Board Member typified the problem of trying to convince people who, because of their own particular background, cannot escape from value loaded judgments, even when confronted with empirical evidence. The result was that highly probable avenues of understanding the error mechanism never found their way into NTSB reports.

Examples of design effects on the perception/decision/reaction process, *i.e.* design-induced error, are so numerous that they are difficult to discuss without leaving the impression the items mentioned are singular deficiencies. Accordingly, the reader is counseled to consult human engineering textbooks;[14] design safety handbooks;[15] or handbooks similar to the latter which are part of every major manufacturer's engineering work process. These documents, as well as accident reports and analyses such as the ADIPE report, chronicle the bitter lessons of the past. Suffice to say here, a perception oriented design-induced error could be as simple as not providing sufficient illumination or attention getting characteristics for a warning light. Design-induced decision errors could, as mentioned earlier, emanate from inadequate pilot or maintenance handbooks. Or to take a more hardware-oriented example, consider a control system prone to "pilot induced" oscillations. At a given stick force and direction, the pilot decides the aircraft is going where he wants it to go.

Insufficient anticipatory information is transmitted to him, however, to preclude overcontrolling and his memory influence in the decision process cannot compensate for what else is going on in the control loop. Design affecting the human reaction mode could be as simple as the length of the control stick. Some years ago, a fighter aircraft was actually designed that required the pilot to extend a telescoping control stick so increased leverage (force) could be applied to the controls to recover from a spin.

AVOIDING DESIGN-INDUCED HUMAN ERROR

This brings us to the principal lesson people should appreciate when discussing human error, design-induced, or otherwise. There is a difference between what a man can do and what he will do—what he is capable of doing and what he is expected to do or what someone wants him to do. Such vagaries in performance are normal human behavior to some level of probability, and it is a rare case indeed that a given human error is a first time occurrence.

As a matter of fact, man has a remarkable capability to compensate for inherently hazardous situations, at least up to a point.[16] His awareness of the hazard actually produces a higher level of safety than might be expected theoretically, all other things being

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[14] *See, e.g.*, HUMAN ENGINEERING GUIDE TO EQUIPMENT DESIGN (H. Cott and R. Kinkade eds. *Govt. Printing Office*, 1972).

[15] USAF SYSTEMS COMMAND, SYSTEM SAFETY, AFSC DESIGN HANDBOOK, DH 1-6 (Wash., D.C.).

[16] *See, e.g., Address, supra* note 13, at 6-7.

equal. This, in turn, accounts for the difficulty in differentiating design-induced error from "pure" human error. A pilot can live with and compensate for a poorly human-engineered fuel selector valve, for example, until that one time when other tasks, memories, or cues interfere with the job of selecting a particular fuel tank— but again, this is a matter of normal human behavior.

The criteria for whether some error is design-induced would seem to depend upon a determination that a more error free system could have been designed initially and reasonably according to known human factors principles. The "system" in this instance must encompass both the vehicle and the man, with the man being part of a group of people with certain qualifications for his presumed control role. Also, careful study of the environment must be made to make certain that external conditions were not present for which the machine was not designed, or in which the man was not supposed to become involved.

The techniques for avoiding design-induced human errors are quite well known even though not universally applied. They include:

- Task Analyses as part of the design process.
- Good human engineering of controls, displays and workspace.
- Hazard Integration Analyses using mockups and simulators which should be a continuing part of the design process.
- Job Hazard Analyses wherein typical operational people are used in a real world situation in a last phase effort before releasing a system for general use.
- Accident/Incident Investigation to assess whether the assumptions made during design were valid.

Optimally, an interdisciplinary team would be used in these efforts, comprised of engineers, psychologists, medical personnel, operations specialists, and safety personnel.

CONCLUSION

Throughout this article, most examples and references to human error were cited from a pilot error point of view. This was a matter of convenience, not singular intent. As events of the past several months have highlighted, there are other classes of people involved in aviation safety "error"; for example, air traffic controllers. These human errors, too, can be minimized, if not eliminated, through design.

Unfortunately, the pilot-error syndrome has had most of the emphasis in the past. This is "unfortunate" for two reasons. First, an oversimplified view of the system is taken if the pilot or any other single person is examined as the presumed savior or perpetrator of aviation accidents. Secondly, by emphasizing pilot error, performance of other key groups, such as air traffic controllers, has not been investigated or studied to the degree it should have for optimum safety balance within the system. The same capabilities and limitations in human behavior apply to air traffic controllers, maintenance personnel, operational managers, and others, as to pilots. The need for understanding human error phenomena is universal if accidents resulting therefrom are to be minimized.

It does not follow that, if an accident is ascribed to pilot error, controller error, or anybody else's error, the best remedial action rests with the person or persons in the same category. It may be the only short-term solution available; but a much more time- and cost-effective approach is to look for the design approaches that can be used to minimize if not eliminate the problem over the long run.

As stated at the beginning of the article, human error is a fascinating subject, and now we can cite another reason why: we have such a long way to go to apply the knowledge we already have towards the prevention of human error accidents.