A SURVEY OF THE STATUS OF AND PHILOSOPHIES RELATING TO COCKPIT WARNING SYSTEMS

(NASA-CR-152071) A SURVEY OF THE STATUS OF AND PHILOSOPHIES RELATING TO COCKPIT WARNING SYSTEMS (Cooper (George E.), Saratoga, Calif.) A03/MF A01 CSCL 05E
N78-13746
Unclas
G3/54 55041

by

George E. Cooper
22701 Mt. Eden Rd.
Saratoga, California 95070

Contractor Report
Prepared under Contract NAS2-9117
June 1977
Submitted to
NASA Ames Research Center
Moffett Field, California 94035

TABLE OF CONTENTS

	Page
INTRODUCTION	
Background	1
Statement of the Problem	1
Program Objective	2
Method	2
RESULTS	3
DISCUSSION	6
Generally Accepted Guidelines	
General	6
Auditory	14
Visual	18
Guidelines Recommended by a Few But Overlooked by Most	
General	21
Auditory	22
Visual	24
Guidelines with Mixed Reaction and Acceptance	
General	26
Visual	27
Tactile	30
ANALYSIS AND COMMENT	30
RECOMMENDATIONS	40
REFERENCES	43
BIBLIOGRAPHY	44

A SURVEY OF THE STATUS OF AND PHILOSOPHIES RELATING TO COCKPIT WARNING SYSTEMS

George E. Cooper
22701 Mt. Eden Rd.
Saratoga, California 95070

INTRODUCTION

Background

The development of the airplane has been marked by steady improvement in performance and mission capability. This improvement has been accompanied by more and more complex systems, the control of which requires that the flight crew be furnished with an ever-increasing number of cockpit instruments, controls, displays, and switches.

The industry has responded to problems related to the management of these systems by providing a variety of warning and monitoring devices. In many cases a warning sound or light is introduced to alert the pilot to a situation that requires his attention and that otherwise might go unrecognized for some period of time. General standards have evolved in which a different sound is used for each audio warning. Often the louder or more distracting sound indicates the more serious condition; the use of color-coded lights (red to indicate the need for immediate action and yellow for delayed action) also categorize potential hazards and the appropriate responses. The general practice has been to add warning or cautionary devices one at a time as needs have been identified. This has led to a proliferation of warning sounds and lights which, in some cases, may have become counter-productive.

Statement of the Problem

The ensuing piecemeal development of cockpit caution and warning (c/w) devices has come about with only isolated standards or guidelines being established for commercial aviation. Whatever standardization may have been achieved is probably due in part to the establishment of military specifications, but the guidance they provide has little effect on the proliferation of c/w devices in the transport cockpit. Such standards as exist within the FAR's are scattered and unrelated largely because they have been developed individually to meet apparent specific needs at the time and without consideration of overall cockpit design. The military specifications have gone somewhat further in consolidating basic standards for such cockpit systems and the human factors elements which relate to them, but cognizant military personnel feel that even these need revising.

There is no way of knowing how many aircraft accidents have been prevented by existing c/w systems; certainly some of these systems have been at least partially effective in preventing accidents. On the other hand, there are a number of accidents which can be attributed directly or indirectly to the c/w systems themselves. A number of these, of course, are related to false or erroneous warnings, especially when these occur in a way that distracts the crew at a critical time, that is, when the crew's complete attention should be devoted to managing the aircraft and making decisions. One example is the case of a false stall warning that occurred during takeoff. The warning sound was so loud that the crew could not communicate, and the result was an attempted abort with insufficient runway remaining.

Cockpits of some modern transports have been compared to the interior of a cathedral because of the maze of colored lights required to convey the multiplicity of cautions and warnings. Two basic questions appear to be evident: First, is there any way to reverse the trend toward proliferation of warning and cautionary devices in the cockpit? Second, based on what we know today, are there any standards, guidelines or criteria that can be applied to the design of warning systems in future cockpits to improve their effectiveness?

Program Objective

The primary objective of the NASA program reported here was to take a broad look at current cockpit c/w systems, to examine industry philosophies regarding c/w system design, including current efforts to improve them, and to identify guidelines that are currently in use, delineating those which appear to have general acceptance, those which are considered ineffective or erroneous, and those with which there is broad disagreement as to their validity. The results of the survey are intended to provide guidance for NASA's research and development programs in human factors.

Method

In order to accomplish these objectives, a broad industry survey was undertaken during which major airplane manufacturers — those concerned with large transports, general aviation, and military aircraft — were interviewed. Also included were several military and NASA establishments that have cognizance of cockpit design, research, and aviation safety. Finally, a manufacturer dealing specifically with aircraft instrumentation and electronics was consulted. A summary of survey-related visits is shown below (a complete listing is provided in the Bibliography).

Transport aircraft manufacturers	
Domestic	4
Foreign	3
Military aircraft manufacturers	4
General aviation manufacturers	2
Instrument and supporting systems manufacturers	1
Government agencies	
Regulatory, R & D	2
Military Service, Safety, R & D	4
NASA Centers, R & D	2

The approach taken in arranging each visit was to inform the company of the purpose of the visit and to establish a mutually acceptable date. Upon arrival, the interviewer would explain the purpose of the visit, indicate that his interest was in the company's philosophy with respect to c/w systems, its specific views with respect to standards and guidelines they had found acceptable as well as those they had found unacceptable, and in defining areas of conflict where different solutions and opinions were evident. It was reasoned that as a result it should be possible to define specific questions and problems as well as possible approaches to their solution. It was pointed out that the purpose of the survey was not to enable NASA or the FAA to design a system for a future aircraft but rather to clarify problems and questions, solutions or answers to which were needed to guide NASA research and aid industry in designing more effective cockpits with respect to c/w systems. So that the opinions and recommendations obtained would clearly represent those of the persons being consulted, the interviewer made a specific effort not to introduce his own viewpoint into any of the conversations. It was also hoped there would be consensus with respect to some standards and guidelines, thereby establishing some overall acceptance and eliminating the need for research of some items.

In each case the discussion focused on the equipment or technology available to the company in question and on those directions they felt it important to follow. A standard list of questions was not used, but in almost every case the discussions centered on audio, visual, and tactile c/w devices; a "general" category was used for the items less specific in nature. This report discusses the subject by combining or contrasting the inputs from various organizations under each of these categories.

RESULTS

Tables 1, 2, and 3 list those guidelines or philosophies that were specifically mentioned during the survey program. Those mentioned most often in the separate interviews are listed first, with the remainder following in approximately decreasing order. Guidelines with general acceptance are given in table 1; general acceptance means that the guideline as stated was supported by the majority of those interviewed and that very little, if any, opposition was voiced. Table 2 lists those guidelines that were strongly supported by a minority, with few or no contrary opinions expressed by others;

this means only that these guidelines were not mentioned by the majority, not that there is no controversy associated with them. Table 3 lists those guidelines that received mixed reactions; they are listed separately to indicate that a marked difference of opinion exists. More than one-third of those interviewed expressed some opposing view.

TABLE 1.- GUIDELINES WITH GENERAL ACCEPTANCE

General

1. "Flight crews of current transport aircraft are overwarned."

2. "Immediate action warnings should be kept to a minimum."

3. "Both an audio warning and a visual indication of failure are generally required."

4. "Reliability of c/w systems is extremely important."
"Warnings or signals that actuate too often are useless as c/w devices."

5. "Standards or guidelines are needed for warning systems."

6. "Warnings should be prioritized; some warnings should be inhibited during critical phases of flight."

7. "New Warning system additions to the cockpit should be thoroughly evaluated before being placed in service."
"Full mission simulation should be used to study the human factors."

8. "It should be possible to cancel most warnings."

9. "Electronic display, computer logic, and checklist monitoring are desirable advances, as is the positive trend toward computers and more automatic systems."

10. "Air crew workload is often too high."
"The major air crew task is to fly the airplane" (not to operate systems).
"More flight engineer duties and aircraft systems should be automated."

Auditory

1. "Audio warnings or signals should be limited to four or five."

2. "Continued loud sounds tend to incapacitate."

3. "Voice warnings are desirable."
"It is acceptable for all audio warnings to come from a single source and to be electronically generated."

TABLE 1.- Concluded.

Visual

1. "A central warning system is needed in the cockpit."
   "All visual warnings should be concentrated within a 30° visual cone."
   "Anything displayed on the central warning or caution panel must also be displayed somewhere else."

2. "A darkened cockpit is favored for normal operations."

3. "Lighting intensity and contrast are a serious problem in c/w systems."

TABLE 2.- GUIDELINES RECOMMENDED BY A FEW BUT OVERLOOKED BY MOST

General

1. "Configuration warning is necessary for certain flight phases."

2. "Most urgent warnings should be related to the control involved."

3. "A requirement exists for additional warnings, that is, attitude, turbulence, wind shear and collision avoidance."

Auditory

1. "Audio warnings should be used for pilot error situations only."

2. "A radio override switch is needed to reduce interference by c/w systems."

3. "Voice warnings should be advisory in nature."

Visual

1. "The value of large, easy-to-read lettering or messages in a c/w system has been under-emphasized."

2. "A third color in addition to red and yellow is needed in caution/warning systems."
   "The use of all colored lights in the cockpit should be standardized."

TABLE 3.- GUIDELINES WITH MIXED REACTION AND ACCEPTANCE

General

1. "An improved c/w system for retrofit is desirable."

2. "Reverse the trend toward teaching pilots basic systems only (BSO), that is, procedures only without a thorough knowledge of the aircraft systems."

Visual

1. "A master warning light should be used."

2. "The annunciator panel should display only system malfunctions and not pilot errors."

3. "Flashing lights should be used in c/w systems."
"Flashing lights are excellent attention-getters but are seriously distracting."
"Variation in flash rate should be used to indicate criticality."

Tactile

1. "The use of tactile warnings should be extended in order to diversify the inputs to the pilot."

DISCUSSION

In the following sections, the guidelines and philosophies are used as the basis on which discussion is conducted under the subheadings of general, audio, visual, and tactile. Where helpful in illustrating a point, actual examples drawn from the interviews are also presented. Recommendations for research or future study derive from the interviews.

Comments or conclusions expressed in this section of the report are generally from the persons interviewed, unless identified otherwise. In the following Analysis and Comment section conclusions of the author are also included.

Generally Accepted Guidelines: General

1. "Flight crews of current transport aircraft are overwarned." There was almost universal agreement with this statement. The only exception found was with the manufacturers of the smaller general aviation aircraft which so far have escaped the proliferation of warning and alerting lights and sounds. These manufacturers, however, did recognize the beginning of a trend in this direction. They were more concerned, however, about

increasing regulation, which requires more and more instrumentation and special equipment to operate in today's airspace. There were few who thought more warning devices were needed. It was apparent, however, that they were anticipating future development for collision avoidance, turbulence, altitude, and windshear warnings. This comment was therefore interpreted to mean that new requirements for warning and alerting devices may be required but that in the overall picture the total number must somehow be reduced and/or incorporated in the cockpit with more concern for the human factors involved. One manufacturer felt that we could be creating more hazards than solutions by the addition of more and more warning and alerting devices. Another opinion expressed was that aircrew members are becoming warning-dependent because of the trend toward providing a warning for every possible pilot transgression or error. One manufacturer indicated that this appeared to be associated with the trend toward teaching pilots the basic systems only, that is, teaching procedures without a thorough knowledge of the aircraft systems, and that this was a fundamental error. This subject is further discussed later in the section on Mixed Reaction and Acceptance.

2. "Immediate action warnings should be kept to a minimum." The implication here was that too many immediate action warnings will render immediate response impossible or force pilot action that could be in error. A maximum of 10 was referred to. Most comments were not specific but endorsed the concept. While it was not always stated in the same words, there was a desire expressed to see a drastic reduction in the number of red lights or other immediate action warnings. With one transport aircraft, the red and yellow annunciator panels were separated, and each pilot had his own red emergency warning panel located at the side. It was necessary for both the pilot and copilot therefore to look to the left or right side panel to ascertain the problem after first being alerted by his own centrally-located master warning light. The large number of red lights in this panel was considered quite undesirable.

One Air Force spokesman would like to see the large amount of prime instrument panel space now devoted to c/w lights reduced. The trend toward the master warning light and central panel (with up to 100 lights) is dictated by a requirement for some rational organization which can be better managed by the crew.

3. "Both an audio warning and a visual indication of failure are generally required." It was generally agreed that more than one channel of input should be used to assure reception of a warning by the crew. The most commonly used combination is audio plus visual, but in this context a tacile warning could be used with either visual or audio in certain cases. One concept advanced for the use of multiple warnings was that the audio signal alerts and the visual signal identifies the problem. There appears to be merit in this concept, but there are others who recommend the use of flashing lights rather than audio signals for alerting the pilot. In the author's opinion, there also appears to be merit in considering the alerting function as separate and distinct from the information and action function of a c/w system, but this will be discussed further in the Analysis section.

4. "Reliability of c/w systems is extremely important."

"Warnings or signals that actuate too often are useless as c/w devices." Nuisance warnings, whether caused by unreliable systems or by design error, contribute to a pilot's ignoring an indication when it is a real one. The example mentioned most often in this regard relates to the altitude alert, wherein the alert signal, both light and tone, are excited as much as 1000 to 1200 ft prior to reaching the set altitude. This was considered an objectional feature by a great majority of those interviewed and considered desirable by only a very small percentage of pilots. If a warning sounds too often, it was pointed out, the pilot develops the habit of "punching it out" without thinking, and it loses its value. A few pilots learn to depend on it for preventing altitude overshoot so that failure to operate can be more serious. An auto-pilot disconnect, which actuates an audio warning on each frequently occurring disconnect also was noted as losing its value. True reliability, therefore, includes the human element as well as reliability of hardware.

One of the simpler methods of ensuring reliability in the human element lies in not having systems that "cry wolf." Such is the case when the crew is forced repeatedly to punch out a light or silence a warning sound or disregard nuisance indicators. Systems that have been so identified include the altitude alert, the GPWS during its initial period of operation, and lights that flash during engine start or normal system operation. A simple solution for improving the latter has been obtained by introducing a short time delay (50 to 75 msec) in the indicating lights of a master caution or warning panel. This eliminates spurious lights flashing due to aircraft acceleration or momentary switching of electrical systems. One company which employs this method indicated that a somewhat longer time was required in the case of low oil pressure indications. In spite of widespread criticism of the GPWS, one manufacturer has documented numerous instances where the device has not only prevented potential accidents but has also detected instrument approaches that were marginal with respect to initial approach terrain clearance. Causes of nuisance warnings have been determined and corrective action taken such that they are now reported by one GPWS manufacturer to be almost nonexistent (ref. 1).

Avionics reliability was generally praised and considerable credit given to the RTCA committee which established the criteria. The current practice of packaging cockpit instruments and avionics separately and developing each cockpit from the desired "modules" has certain reliability benefits, in that failure of one subsystem affects only that element. The additions of altitude alerting and the GPWS are recent examples. The modular concept, however, does have certain disadvantages. One is the adverse effects on standardization. One company pointed out that it must be prepared to install any one of 18 different ADI's in its aircraft, depending on customer choice. Possible adverse effects can also occur with c/w systems in that simultaneous operation of several warnings can result in delayed response by the crew because they must first sort out the various indications and formulate decisions before taking action. This is in conflict with the strong recommendation for some method of prioritizing warnings. The Air Force now recognizes the need for total system analysis if overall system reliability is to be obtained. Such a system reliability study is currently being conducted for the Category III landing.

The high reliability achieved with avionic systems to date was given high praise and specifically credited with the current success of the head-up display, which combines and integrates a variety of information, that is now in use by the military. One problem which apparently has not been completely solved is how to remove unreliable information from a HUD. The central air data computer (CADC) was noted as a system that has become extremely effective because of its high reliability. One fighter aircraft has been flying nearly 4 years without a single failure in its prototype.

Some of the simple systems mentioned for improving reliability are the use of dual lamps in c/w panels for redundancy, the use of a systems' test panel wherein the systems can be tested on the ground or during preflight, and fail-safe circuitry design utilizing a logic system that provides detection, through a test switch, of a broken wire or sensor problem.

New, sophisticated aircraft also contain an additional system for improving overall reliability. One such system is referred to as the BITS (built-in-test-system), which enables an operator to trace faults throughout a system and to isolate causes of specific failures that may be indicated on an annunciator panel.

The cause of a large family of nuisance warnings was illustrated during discussions regarding space systems with astronauts and other personnel. This was a particular problem during the Apollo program wherein many warnings and cautionary indications plagued the operation because the limits on many systems were set too tight. As a result, as each system went out of limits, a warning would occur. In a strict sense, then, most Apollo c/w's actually were out-of-limit indications, nuisance warnings, rather than true faults.

This problem was noted to have two possible solutions: (1) To employ a built-in test system wherein an operator can interrogate in minute detail the various elements of a system to determine where the fault lies, and (2) after using the test system to determine when a fault is merely out-of-limits a small amount, a capability is provided allowing in-flight adjustments to the system to reset limits and thereby reduce nuisance warnings. The astronauts with whom this was discussed expressed some concern about making these actual adjustments in flight for fear of "fouling up" a system. A conflict therefore exists between continued acceptance of such nuisance warnings or acceptance of the risk involved in making in-flight adjustments to established system limits.

The space shuttle will use a special status panel to isolate faults and determine the out-of-limits condition. It was pointed out that a dedicated computer was required for such a software system and that the computer must have a very large capacity for such a complex task. With respect to redundancy in display elements, a triple CRT display will be available wherein any c/w message can be shown on any one of three displays.

The conflict between the continued use of separate, modular systems in the cockpit versus combining these into a single unit and accepting automatic prioritizing has been mentioned. Reliability of the single voice warning unit which contains multiple warnings with automatic prioritizing was reported to be very high, partly because many internal failures can occur before readability of the message is lost.

5. "Standards or guidelines are needed for warning systems." Throughout the survey, it was apparent that military standards regarding cockpit design and human factors considerations (Mil. Stds. 1472 and 411D, Aircrew Station Signals, Human Engineering Design Document) have had a significant effect on the development of many warning systems in both civil and military aircraft. Of those commenting, practically all specifically favored the development of greater standardization. A few, including manufacturers of general aviation aircraft, were concerned that this might lead to additional regulatory requirements. A surprisingly high percentage of comments favored the adoption of standards or guidelines for cockpit warning and alerting devices for civil application. While no detailed comments were obtained nor study made of the FAA standards, the feedback obtained indicated that Federal Air Regulations (FAR) pertaining to cockpit warning and alerting were widely scattered and more restrictive than helpful. Nevertheless, one transport manufacturer suggested that the FAA should take the lead in achieving greater standardization in this area for civil aircraft.

It was apparent that military specifications are not applied uniformly by all military contractors. This suggests that the military specifications function effectively as guidelines to effect a degree of standardization without seriously impairing new development. It appears probable to the author that this could also reflect differing viewpoints of system project officers (SPO's) or else the lack of sufficient justification being presented by the manufacturer for a waiver or deviation. Air Force personnel confirmed that the human factors document, Mil. Stds. 1472 (ref. 2) was a very general one and did actually serve primarily as a set of guidelines for the designer. The Air Force also indicated that there was a current effort under way to revise those parts of Mil. Stds. 411D relating to "Aircrew Station Signals" (ref. 3). The current effort recognizes the need to include the rationale behind the specification.

The Boeing Company, under an FAA contract, has done considerable work in defining requirements for an independent altitude monitor. Included in this study is a very extensive literature search that compiles a great deal of basic human factors data that is fundamental to cockpit design from a man-machine integration point of view and could assist in development of standards for civil aircraft. It includes such items as stimuli response data, alerting philosophy, and concepts (ref. 4).

An effort is currently under way by the S-7 Committee of the Society of Automotive Engineers not only to revise SAE Standards for civil aircraft but also to provide design guidelines for improved future c/w systems (ref. 5). There would appear to be distinct advantages in maintaining some level of coordination between the S-7 Committee effort and the military.

Currently, this occurs through common civil-military contractors. While identical standards are probably not obtainable and may not even be desirable, there are many areas where, because of basic human factors involved, there will be agreement with respect to guidelines and criteria.

6. "Warnings should be prioritized; some warnings should be inhibited during critical phases of flight." Both of these guidelines also relate to the reduction of emergency warnings to less than 10. There was general agreement that an individual crew member can handle one emergency at a time and that additional extra warnings distract him from the task at hand. As a result, there was unanimity of opinion that it should be possible to cancel most warnings. Some means, however, must often be retained in certain situations for decision-making and prioritizing by the crew.

On a number of new aircraft, such as the Concorde and A-300, a takeoff inhibit mode is provided where the pilot may cut out all but a few critical warnings during the takeoff phase. Such a system reduces the potential distraction during a critical period and eliminates the possibility of aborting the takeoff without sufficient reason. On one foreign aircraft, fire warning is actually inhibited during the takeoff phase. One contributing factor has been the large number of false fire warnings. Another was concern about the possibility of shutting down the wrong engine, which has been and often still is a possibility. Even conducting cleanup checks on the engine after a shutdown has a certain potential for affecting the wrong engine. Finally, it was concluded that an engine fire can usually be better handled in the air than on the ground during an abort. This remains a controversial subject, however.

Inhibit capability is, in reality, a form of prioritizing, and the ability to cancel certain warnings is a manual means of inhibiting. While there was some concern about carrying prioritizing too far, the capability of inhibiting during certain mission phases appeared to be universally acceptable. The concern relates to the fact that the pilot should always retain the final authority for establishing priorities. With multiple failures, however, it would appear desirable that he receive additional help. An extreme example of this would be the case involving Apollo 13 when an emergency caused by the explosion of an oxygen bottle in the command module created a "domino" situation which resulted in the entire panel being alight with warning and caution lights. The complex effects of this emergency could be sorted out only by use of a team of experts working with the backup vehicle as a simulator back on earth. By careful simulation, determining causes and effects, the scientists, engineers, and technicians on the ground were able to determine the extent of the damage, what systems were affected, and the risks involved either in continuing flight or returning to Earth as soon as possible. The point is that it was not possible to deduce from all the lights exactly what proper emergency action should be.

Once inhibiting is accepted as a means of reducing the number of warnings the pilot is subject to, there are several ways open for its implementation. One is through manual inhibiting by flight phases, relying on crew action for activation. The other is by use of a computer which uses preplanned logic that will respond to an order of priorities in presenting warnings as well as determining the level of warning that needs to be displayed. By this it is meant that failure of a first system might result in a caution, whereas failure of a second system would result in an emergency warning. This concept has been carried forward even further with a proposal called PAWS (Phase Adapted Warning System) (ref. 6). In this case a switching logic module receives information from the central annunciator panel and some other sensors (i.e., airspeed, altitude, etc.). It then can produce one of three possible outputs to the warning lights: red for immediate action, yellow meaning "caution or delayed action," or a third signifying "hold," but without any audio or visual display or action signified.

7. "New warning system additions to the cockpit should be thoroughly evaluated before being placed in service."
"Full mission simulation should be used to study the human factors."
Due to evolutionary development and piecemeal additions of c/w items, insufficient attention has been devoted to the human factors aspects of the resulting cockpit in terms of overall workload requirements and pilot acceptance of the c/w system. While testing of some individual components may have been extensive, the resulting combinations have been subjected only to the operational evaluation obtained from actual line or service use. The majority of those interviewed expressed the need for a more thorough evaluation of proposed changes to cockpit warning and alerting systems before placing them in service.

It was felt that if this had been done, many of today's problems would have been identified and analyzed much earlier, thereby enabling either correction or discontinuation of unsuitable c/w methods. In addition, a degree of testing in the operational environment is usually required to ensure system reliability and elimination of most nuisance warnings.

Although the comments received differed in form, they supported, in general, this guideline. Some were more specific in stating that such an evaluation program must be objective in nature and should be conducted by an unbiased group.

It must be stated, however, that there was evidence of considerable testing being done by manufacturers, military agencies, and others to guide specific cockpit designs and acceptance of new technology. The cases in which these efforts failed or were incomplete seem to be related to the lack of the total workload concept in the evaluations, such as would be provided by full mission simulation. Recent studies have shown that such methods do have the capability of providing realistic workloads and, more important, of eliciting the same actions, reactions, and decisions from the flight crew as the actual flight task would.

8. "It should be possible to cancel most warnings." This guideline stems also from the proliferation of warnings and applies to both the visual and audio systems. Any device which is sufficiently attention-getting to alert a crew member also has the potential for creating a highly distractive environment. This conflict appears to many to be resolvable only by

providing the pilot with a means of cancelling the warning signal once it has accomplished its primary purpose of alerting. Some of those interviewed were concerned that a warning which cannot be cancelled except by correction of the fault has a tendency to force the pilot into precipitous action which might be erroneous. Extremely loud or visually distracting alerting systems can interfere with cockpit communication, decision making, and crew coordination. In such cases, cancellation of the warning becomes essential prior to taking corrective action.

9. "Electronic display, computer logic, and checklist monitoring are desirable advances, as is the positive trend toward computers and more automatic systems." These guidelines will be discussed together. While these trends are recognized and appear acceptable to the industry, there is some concern about what the limits to automation and sophisticated computers really are.

Recent work by Boeing, known as the Automatic Systems Monitor (ASM) program, in which CRT's were utilized in a 737 simulator study to explore the replacement of basic engine instruments and the application to providing better checklists, is very encouraging. This program also made use of full mission simulation as an evaluation technique. The results of the Boeing work also appear to have influenced the design of the space shuttle cockpit, in that three CRT's are being used there as a means of improving the information display for the astronauts. The astronauts who evaluated the Boeing program were particularly impressed by the way information was split on the CRT, providing not only basic warning information in the upper half but also displaying, in the lower part of the display, the action to be taken. Another concept employed in the Boeing ASM program included the provision for displaying the layout of any given system, together with associated procedures, in response to an inquiry by a pilot. It was emphasized that much work is still required on how best to display the information so that the pilot can rapidly assess the problem and appraise what he is doing. The mere lifting of tables and instructions from manuals is not considered to be an acceptable solution.

The use of computers will be vital to future c/w systems if such apparently desirable features as prioritizing and inhibiting by phase of flight are adopted. It was also pointed out that the big advantage in the use of digital equipment lies in its self-monitoring capability, available without additional equipment.

In modern, sophisticated vehicles such as the space shuttle, a limitation in computer capacity can be encountered which places practical limits on the extension of caution and warning systems to handle everything considered desirable. Complex computer systems have been employed on recent aircraft, such as C-5 and B-1, to enable isolation of faults in response to c/w indications. While problems have been encountered in the use of such complex systems during operational phases, indications are that, given sufficient support, computers will play an important part in enabling on-board isolation of the detailed causes of c/w indications. Central integrated test systems, for example, are reported to be extremely effective and reliable in this regard if properly maintained. Such systems become more important as the operation of more and more aircraft systems is conducted automatically, leaving fewer indications to the crew, other than that a fault exists within a given system.

10. "Air crew workload is often too high."
"The major air crew task is to fly the airplane" (not to operate systems).
"More flight engineer duties and aircraft systems should be automated." The significance of the high aircrew workload under certain flight conditions and its effect on crew-member response to the c/w systems is illustrated by the following example. During takeoff, a senior pilot was informed that an engine would be cut on him at some point for his evaluation of handling characteristics and safety. During the takeoff an actual fire warning occurred, but the pilot was so intent on handling the engine out that he failed to recognize the engine fire, even though all warnings were provided. Other examples were noted in which pilots failed to hear warning sounds or to observe warning lights under conditions of high stress and concentration. This, of course, was a primary reason for the recommendation that multiple channels be used to provide c/w signals. The conclusion is evident, therefore, that under high stress and workload conditions there is probably no way that one can be assured of a warning being recognized and acted on properly by a pilot. Crew coordination and monitoring procedures, therefore, assume a much greater importance. There can be no doubt that this fact has indirectly led to some of the existing problems, such as the use of many loud audio tones and sounds, and centrally located flashing or steady red and amber lights. All were designed to insure catching the pilot's eye or ear, but primarily causing a distraction and adding to the workload.

Generally Accepted Guidelines: Auditory

1. "Audio warnings or signals should be limited to four or five." Of all recommendations made by those interviewed, this one was mentioned most often. One concludes that there is universal consensus that audio warnings must be reduced in total number and in types of sounds.

It was not uncommon for aircraft to have 10 to 12 different audio sounds, and in some aircraft the number of tones exceeded 30 or 40. There is little wonder, then, that concern was expressed about identifying a given tone with a given warning. It was pointed out that some sounds might be reduced by inhibiting them except for a critical flight regime for which the warning was needed. Because of the many audio signals in use, it was recommended by some that preflight familiarization with them was essential. Others were not in favor of this, believing that this was more distractive than helpful, and as a solution recommended the overall reduction of sounds.

Military Specifications provide no standards in this regard. As a result, innumerable pilot evaluation programs have been conducted to determine which sounds will be used on each aircraft. The result has been a proliferation in number as well as in different types of signals throughout the industry.

One solution that has been incorporated in some recent foreign transports has been the use of a single alerting tone (gong) for either all warnings and cautions or just warnings. The only objection found to this was the fact that many feel it important to retain, because of their long history of use, the bell and horn used for fire and landing gear warnings.

It was pointed out that a reduction in the number of audio warnings could be effected by eliminating all audio signals from cautions or lower level advisories. This, however, remains controversial. Even if a single alerting sound is used, there was a question of whether it should be steady, intermittent, or automatically cancelled after a given period.

There was a plea from a significant number of those interviewed for development of some standards in this regard; it was recognized that some additional objective evaluation program might be necessary.

2. "Continued loud sounds tend to incapacitate." It was pointed out that, if a pilot is unable to cancel or diminish a loud alerting sound except by correction of the fault, he is very apt to be pushed into precipitous action, thereby inadvertently taking incorrect action.

This philosophy of continued loud warning sounds was frequently emphasized and has led to certain recommendations. One is that the pilot should be able to inhibit or cancel any audio tone. Another is that the pilot should have control over the intensity of the sounds. Both of these have been factors in known aircraft accidents. Current military standards require that any warning sound must have a sound level higher than the maximum ambient noise at the warning frequency. While this has a certain rationale, it could require sound levels that are highly distractive and which could incapacitate the crew. While the ability to cancel a warning has already been discussed as highly desirable, the provision of an intermittent signal, for example on 10 sec, off 10 sec, was recommended as a solution in some cases, since it would at least provide brief periods of freedom from the distractive sound during which coherent thought could be resumed. Recommendations were also received that a 10 sec audio signal should be sufficient for alerting purposes and that it should be automatically cancelled after this or some other experimentally determined interval. Conflicting opinions were also received with respect to an audio signal for autopilot disconnect, which often was considered a nuisance. This was partially resolved, however, by the difference in consequence and hazard associated with such a disconnect on different aircraft or flight regimes.

3. "Voice warnings are desirable."
"It is acceptable for all audio warnings to come from a single source and to be electronically generated."
The problems associated with having too many auditory signals no doubt enhances the desirability of verbal warnings. The problem of associating various sounds in audio signals with a particular failure is eliminated if a voice message is used to tell the pilot clearly what has happened. The

Air Force indicated that research has shown that there is a 6 to 9 sec improvement in recognition through the use of such direct cues, a concept which they favor highly. There were essentially no objections to the concept of voice warning even though many of those interviewed had no direct experience.

One statement was that pilots want and need more information through the auditory channel. Many pilots themselves concluded that voice is the way to go because a message clearly stated reduces acceptance time, even though they would also want a backup visual identification. Air Force pilots indicate that their heavy reliance on a visual c/w system is simply the result of having too many tones to identify and relate to. Therefore, the direct, simple solution is the use of "plain English" in the c/w system. There were no recommendations for the use of voice warning except in conjunction with some type of visual system. There were few limitations placed on the use of verbal messages in a c/w system except insofar as auditory signals were generally recommended for warnings rather than cautions. Military standards actually limit the use of voice to warnings only and require a separate alerting tone to precede it.

One of the concerns with respect to voice warnings was why, after the initial research and applications in a B-58 years ago, it had never been implemented. In talking with B-58 pilots who had experience with the system, no real objection could be found except that it was a tape-driven system, somewhat unreliable due to development problems initially, but that it had done a good job in supplementing the information from a poorly located caution panel. This panel was located to the left and rear of the pilot and could be seen only by turning the head and looking low and to the rear. One report was that there was a strong tendency to make use of the voice information with the B-58 and to ignore the visual, which is not too difficult to understand considering the location of the annunciator panel.

One study conducted by the Air Force was reported to have shown that 98% of those interrogated favored voice warning, based on their B-58 experience. This is in spite of the fact that this taped system was considered an inferior one and was earlier fraught with reliability problems.

The primary problem of introducing voice in military aircraft appears to be one of paying the added cost of equipping a prototype with a voice system without having data on the benefits. So far, the simplest approach has been to go along with the standard audio-visual warning system composed of sounds and lights. At least two recent Air Force aircraft programs included plans for a voice warning system on a prototype, but both had been cancelled to conserve funds. Voice warnings have been used quite effectively in missile crew work. One difference was noted, however: the conditions surrounding a missile launch represent a more static rather than dynamic situation such as that present during aircraft operation.

There were a number of researchable questions raised involving the application of voice warning. Military Standard 411D specifies verbal warnings for immediate action items only, whereas some responses anticipate a broader application. One concern is the possible interference with or by ATC, other radio communications, or from internal cockpit communications. The earlier proposals to use a feminine voice, which would be more readily recognized and discernible, is no longer valid because of the increasing use of women in control towers and ATC. Electronically generated voices, however, have the potential for being altered through a frequency tone makeup which could be quite different and therefore more readily recognized from the various communications systems. Some concern still exists about the use of proper terminology in voice warnings. The possible differences in interpretation of certain words and phrases by different individuals, particularly by those of different nationalities, were considered to indicate that continuing tests should be conducted until such points are resolved. One concern expressed was that an adequate voice warning system would require a large computer prioritized by phase of flight. This is somewhat in conflict with other opinions which indicate that a small, compact, electrically generated voice system would be extremely easy to retrofit and would have sufficient capability for current transport aircraft.

A serious problem facing the use of a single electronic generator for voice warning appeared to be inertia in the aviation system that must be overcome to enable acceptance of such a change. The need for prioritizing also appears to be very important if the full capability of electronic voice is to be achieved. Currently there are a number of impediments to the adoption of prioritizing. One is the present trend toward the modular development of electronics in separately packaged boxes which are not as conducive to prioritizing and could allow simultaneous warnings to be sounded. Assuming as fact the conclusion that a pilot can handle only one warning at a time and must ultimately resort to his own prioritizing in the case of multiple failures, the majority foresaw no serious problem with prioritizing as long as it is done sensibly and the pilot is informed that additional warnings await recognition. The second impediment is the conflict with some existing regulatory requirements dealing with audio signals, including the use of voice, which require resolution. General opinion has been seen to favor a dual audio-visual warning system. A few of those who were most emphatically in favor of voice warning felt that such a system could stand by itself without the visual backup. This is a researchable question requiring justification.

With respect to pilot acceptance, there was strong sentiment expressed that voice warnings should be advisory in nature rather than commanding. Pilots almost universally appreciated advisories such as "Glide slope, glide slope," indicating an out-of-limits deviation, but considerable objection was raised to the command, "Pull up, pull up." This is discussed more fully under the specific guideline on the subject.

In summary, voice warning was recommended strongly as offering a great potential for improving cockpit warning systems, either through retrofit or as part of an advanced system. Unless prioritizing as a concept can be established, however, much of the benefit potentially available from electronic voice generators may not be realized. While some experimental work has been completed giving insight into the basic elements of voice messages, an evaluation study of voice warning, incorporating varied terminology and including other audio signals, both advisory and of a command nature, was recommended.

Generally Accepted Guidelines: Visual

1. "A central warning system is needed in the cockpit."
"All visual warnings should be concentrated within a 30° visual cone."
"Anything displayed on the central warning or caution panel must also be displayed somewhere else."

These statements reflect the necessity for ensuring that visual warnings do not go undetected. The current trend is to place all red warning lights within a 30° cone of vision and to centralize visual caution signals within a central annunciator panel even if this does not lie within the 30° cone. In concept this appears rational except for the proliferation of lights and the need to extend beyond the 30° cone in some cases because of central panel space limitations. This leads in turn to a requirement for master warning lights, either red or yellow, or both. The competition for central panel space is so severe that little or no consistency has been achieved in either the location of warning lights or of annunciator panels. The result has been that most red warning lights are scattered about the forward panel, generally within the visual cone, but separated with some on the glareshield, some on the panel, some on either side of the console. This is also true on fighter aircraft where landing gear warnings are often well outside this cone.

The basic visual warning system philosophy using colored lights follows the arrangement described as follows: Primary alerting is obtained through red and/or amber master lights located within the 30° cone, preferably near each ADI, as a means of catching both the pilot's and copilot's attention. The military specifications, however, require they not be within the basic group of flight instruments. If a master yellow light is used, it merely directs attention to the primary annunciator panel, the lights on which are sometimes referred to as "director" lights because they direct attention to other yellow lights, usually outside the 30° cone. These third level yellow lights are located, as a rule, with the particular system or control to which they relate. In this manner, the pilot's attention is ultimately directed to the specific system which has failed. Supposedly, he will know where this panel is located even though it may be to the rear or on a flight engineer's panel. Arrows are sometimes used to indicate general location of the system in question. These are often located in places difficult to reach or otherwise inaccessible to normal vision.

Additional red warning lights are positioned wherever space can be found on the forward panel or glareshield. As additional emergency warnings are added, more red lights are necessary. On military fighters, the rim of the glareshield is normally used. Panels used for c/w's take on a variety of forms. On some the red and yellow lights are separated by grouping; on others they are mixed, and in some cases separate red and yellow panels are used. If a central location cannot be obtained, quite often either the red or amber panel will be duplicated so that both pilot and copilot have one. A master warning light becomes necessary when some warning lights cannot be centrally located within easy view of either pilot.

In general, the system of warning lights described here, when properly implemented, were noted to be "not too bad," "reasonable," or "acceptable." Properly implemented refers to readable labels or messages on the lights, red emergency lights well located for each pilot, and central annunciator panel also easily viewed by both pilots. This system allows caution and warning systems involving large numbers of lights (30-100) to at least become reasonably manageable.

In order to achieve compliance with the 30° visual cone, it has become necessary on most military aircraft to mix red and amber lights in the central zone. Examination of these c/w lights, which are clustered about the ADI, or at least within this 30° cone, reveals that, with the exception of a master caution light, they relate, on the newer aircraft, primarily to pilot items, that is, pilot failure or error items. This mixture would appear to reflect a guideline suggested by some to the effect that "Only systems malfunctions should be shown on the annunciator panel." While the latest labeled-light concepts employed on the most recent military aircraft were considered generally acceptable, steps for improvement were still requested.

"Anything displayed on the central warning or caution panel must also be displayed somewhere else," was a philosophy also stated in the reverse, which says that any caution or warning displayed anywhere in the cockpit should also be shown on the corresponding central panel. For example, a master warning/caution light might indicate by color a caution which directs attention to a central annunciator panel. Here the system in question (i.e., electric, hydraulic, etc.) is identified by an illuminated, labeled light. Reference is then made to the electrical panel where it becomes apparent that No. 2 generator, for example, is out, and where action, if necessary, is to be taken.

In the case of warnings, it was obviously desirable to reduce the total number of lights involved; for example, in case of fire, a red light comes on in the actual fire handle, which at once identifies the particular engine on fire and tells the pilot where his fire suppression handle is. If not incorporated in the fire handle, good practice calls for illuminating the particular engine fuel shutoff valve which may be located separate from the fire handle. This precludes shutting off the fuel to the wrong engine.

What has not been considered here is the case where all information for alerting, identification, and action may be provided on a central panel — a situation usually unattainable because of panel space limitations — or that requires a computer-generated display.

2. "<u>A darkened cockpit is favored for normal operations.</u>" A cockpit which is alight with any c/w indication during normal operation or without cause is generally considered distracting and detracts from a pilot's ability

to detect change. Several guidelines were recommended for achieving this concept. Do not tell the pilot something that is good by any type of warning or cautionary device. Do not provide any type of signal if whatever is involved needs to be on during any major portion of the flight. Only annunciate when a system is off so that a light would be on only if there has been a failure or something has been turned off which normally should be on.

In general, pilots favor the darkened cockpit concept wherein, during normal operation, no c/w or status lights are showing. There were some exceptions, however; a few pilots indicated they favored advisory lights which indicate that specific modes or conditions were in operation. There may be a real conflict here unless further investigation uncovers some simple guidelines for the use of blue, green, and white indicator lights. This is discussed more fully in a subsequent section.

In general aviation aircraft, which are just beginning to encounter the addition of lights and c/w indications, many of the new lights dealt with navigation equipment. For example, green for all NAV Systems on, white for DME, and additional lights indicating auto-pilot and flight director modes. If the darkened concept is truly valid, some resolution of the extensive use of colored lights in these areas must be obtained.

3. "Lighting intensity and contrast are a serious problem in c/w systems." This appeared to be a greater problem in military aircraft having bubble-type canopies where extremely high contrast occurs due to direct sunlight at high altitude falling across a portion of the instrument panel. Cockpit lighting mockups have often been used to ensure acceptability of the cockpit design. The other problem which also can occur in transport aircraft is that of the high ambient light during a low visibility approach in fog. Comments were received which indicated that, with this high outside light level, interior cockpit lights often were not seen. These problems lead to other controversial questions, such as should the pilot have control over dimming of c/w lights in the cockpit. General aviation aircraft use a straightforward photo-electric cell to sense the ambient light and to adjust the intensity of cockpit lights automatically. At least one military fighter has adopted a rheostat control to allow the pilot to reduce lighting voltage and intensity even further than that normally provided by the reduction from 28 to 14 V in a two-step system. On the other hand, there is concern about giving pilots dimming control through a rheostat because, I presume, of the possibility of a light being inadvertently left dim when it should be bright. Design techniques to eliminate this possibility should be possible. One military contractor indicates that current technology and design practices can and have eliminated the problem of achieving desired contrast by special treatment of the warning light surface. Some contractors felt that NASA should develop standards and techniques for determining brightness, contrast, and color compliance.

Guidelines Recommended by a Few But Overlooked by Most: General

1. "<u>Configuration warning is necessary for certain flight phases</u>." (i.e., takeoff and landing) This recommendation was prompted in one case because over a hundred takeoffs had been made in the wrong aircraft configuration due to a human factor in cockpit design and layout. In this case, if the electric actuator was used for setting the takeoff trim and the hydraulic trim wheel was in another position, the stabilizer would move to the hydraulic setting when hydraulic power subsequently came on, thereby destroying the pilot's initial, supposedly proper, setting. During landing, the primary configuration warning required is the landing gear horn and light. Primary objections to these warnings relate to the fact that on many aircraft they come on any time the throttle is retarded, regardless of flight phase. This becomes a nuisance to the entire crew and a repeated distraction to the second officer. The solution mentioned most often is to restrict landing gear horn to appropriate speed and altitude ranges for landing and reduce unwanted occurrences at other times. A variable wing sweep aircraft was involved in several accidents because flaps were unattainable when selected unless the wings were completely unswept. A landing configuration warning was added that remedied the situation.

2. "<u>Most urgent warnings should be related to the control involved</u>." Whenever the intent of this guideline can be met, it provides a direct cue which, in general, is unmistakable and enables the pilot to react instinctively. Of the warnings related to control involved, the stick-shaker is the one in most general use and the one most accepted as a good example of the application of tactile warning. In this case it is related directly to the control involved. One example of a situation wherein the stick-shaker was not favored was the F-111 in which a rudder-shaker was used instead. In this case the results were far from satisfactory as it was found that, due to improved handling characteristics, many pilots no longer flew with their feet on the rudders throughout much of the flight envelope. A second objection to the stick-shaker concept lies in the concept of vehicles with a stability and control augmentation system (SCAS) wherein a force transducer or pickoff is used to transmit the control input into an electronic control system. It is reasoned that spurious force inputs caused by a stick-shaker would be prohibitive in such a system.

This guideline need not be restricted to tactile warnings but also suggests that urgent warnings should not be lost in the middle of a central or master warning panel. It also relates to the recommendations which were made to the effect that warnings related to pilot control, such as "pull up," should be located close to the instrument that the pilot is using, such as the ADI. As discussed elsewhere, some individuals even go so far as saying that the pilot-error type of warning must be integrated directly into the display being used. If it is related to flight path, then it should be evident in the flight-path control bar or indication; if in heading, then with the heading indication.

Fire warning lights located in the extinguisher handle and system caution (inoperative/failed) lights located at the switch or lever which controls that system are other examples. Where these are not readily visible, that is, where they are outside a 30° cone of vision, for example, some separate means of alerting the pilot is needed. The particular method used may also be a function of urgency.

3. "A requirement exists for additional warnings, that is, attitude, turbulence, wind shear, and collision avoidance." Several recommendations and/or predictions were made to this effect. Of primary concern at this point, however, is the simplification and design of an improved warning system utilizing guidelines that will enable the future addition of such warnings as their need becomes apparent and the technology is provided for their development. In other words, future cockpit design must allow for the incorporation, without adding to the distractions and confusion, of a few more important warnings.

Two examples of other warnings which have been incorporated in response to specific requirements were provided. The Concorde supersonic transport incorporates Mach number and center of gravity indicators and warnings to alert and advise the pilot when approaching established limits too closely. One recent military aircraft uses an auditory signal of varying frequency to warn the pilot of an approaching yaw departure and incipient spin condition.

Comparative warning systems are needed for certain critical instruments. Merely having redundancy in instruments or systems does not ensure prompt recognition and action. It was emphasized that a "comparator system" to provide an immediate alert to the pilot at the controls, is needed on many aircraft in order to reduce to an acceptable level the time required to recognize certain instrument failures. To a degree this has already been discussed under the paragraph concerned with reliability. A requirement now exists for attitude comparators on large multi-place military aircraft.

Guidelines Recommended by a Few But Overlooked by Most: Auditory

1. "Audio warnings should be used for pilot error situations only." This may be related to the guideline that recommends that only system malfunctions should be shown on a master warning panel. This appears to be based on a desire to organize warnings in a more logical way. If one accepts other guidelines, which state that audio warnings should be reserved for emergency situations only, this one implies that pilot error warnings are the most serious. This, of course, is not the case, as minor human errors and misunderstandings occur through most operations but are recognized and corrected before leading to more serious problems. There is some question whether this guideline could be accepted and still not conflict with others which may be more important, such as reducing the total number of audio warnings or confining audio to emergency situations only. Some ambiguity exists also in regard to whether voice warnings should be included in this guideline and their use thereby restricted. Taken at face value, this would eliminate the use of audio as an alerting device for any system malfunction. This is perhaps beyond what was envisioned, as immediate action warnings can arise from system failures.

In conclusion, there appears to be some basis for this guideline, but at present it is too broad and controversial to be accepted at face value.

2. "A radio override switch is needed to reduce interference by c/w systems." The question raised may be more complex than is immediately apparent. Is the communication to be overridden in order to distinguish the c/w signal, or voice warning? Or is it a cancellation of warning signals in order to maintain communications? It is possible that other than emergency audio warnings should not interfere with radio communication or should be cancellable but that emergency warnings must remain readable in spite of the communications system audio. From the overwhelming desire to reduce audio signals to a minimum, it might be assumed that only those remaining emergency ones need be heard above the normal radio communication. In cases where audio warning signals are piped through the communications speaker or headset, a slightly different situation exists than where only a separate electronic voice or audio warning speaker is used.

3. "Voice warnings should be advisory in nature." From experience with GPWS to date, there was some question as to whether a pilot will respond without delay to a "pull up" command. The majority of pilots apparently like the advisory "glide slope, glide slope," used in the GPWS, and object to the command "pull up, pull up." This led to the recommendation by some that a command like "pull up, pull up" should be preceded by a milder advisory. There were some indications that the large numbers of nuisance warnings which followed the rapid introduction of GPWS into service may have contributed to these objections.

A subsequent study conducted by one GPWS manufacturer (ref. 1), however, provides a more optimistic picture, while still recognizing the human factors involved. A few examples are: "Data on 35 GPWS-equipped airplane incidents revealed that in more than 15 of them the pilot took positive corrective action while under instrument conditions." "GPWS has also detected 14 specific airport instrument approaches that were marginal." "Unwanted or nuisance warnings during instrument conditions have been almost non-existent."

There was evidence during the survey that a warning command without a preparatory advisory was considered undesirable. However, there was an admission that emergency situations requiring immediate action may require a direct cue with a sense of urgency in order to reduce response time. There still appeared to be some reaction against such oral commands as "pull up, pull up," however. The use of a warning term like "terrain" in place of "pull up" has been suggested and may have merit. In any case, it was evident that the number of immediate action commands must be kept to a minimum.

Guidelines Recommended by a Few But Overlooked by Most: Visual

1. "The value of large, easy-to-read lettering or messages in a c/w system has been under-emphasized." Concern was expressed by a number of those interviewed about the readability of some labeled lights, particularly under adverse conditions such as low contrast or turbulence. For example, a problem identified with many annunciator panels was that the lettering was often too small.

Reference was made to one research program involving evaluation by a large number of airline pilots in which a particular prototype area navigation system was used as part of the test equipment. In this case, the lettering used was too small and resulted in the pilots having to shift position in order to distinguish the letters. This difficulty in reading became worse under turbulent conditions and contributed significantly to the time required to insert information and make changes in way points. It was concluded that these features resulted in significant adverse pilot opinion and contributed to a lack of acceptance and realization of some test objectives.

The difficulty of setting exact limits on lettering size for messages is understandable because of the proliferation of annunciator and other lights on the panel and the limited panel space available. A problem of easy readability under normal lighting and non-turbulent conditions is usually the rule, and design is not always controlled by the worst case. Recommendations were obtained from one contractor who had established standards which he felt ensured adequate visibility of labeled lights or messages. These were the use of 1/8-in letters at 28 in from the pilot's eyes and the use of 5/8-in letters for the master caution and all red emergency lights. Military standards only specify that the maximum viewing distance be limited to 28 in.

One interesting approach used in a NASA flight research program involved the use of a digital message line utilizing 1-in letters in the center of the forward instrument panel. The feeling obtained after discussing the use of such large, easy-to-read messages was that there could very well be some previous under-estimation of the benefits resulting from the speed with which visual, written or printed messages could be observed, understood, and acted upon. Obviously, the 1-in. letters may have gone beyond what is practical and necessary to permit rapid interpretation. It appeared highly possible that a reduction in interpretation and action time may result if the messages are provided in large, easy-to-read form, and further work to identify these limits may be desirable. Application in the most flexible form, of course, would be dependent on having a digital computer available for the generation of discrete messages. There was a significant preference established by those familiar with this type of digital message to the same written message on a CRT. Opinions were also expressed in the former program that a simple readout message appeared more acceptable to these pilots than a voice message would be. This may also be influenced by other factors, such as the use of command versus advisory voice messages discussed earlier.

These questions remain controversial. With the printing on annunciator lights often too small, there is an obvious need for a review of criteria in this area.

2. "A third color in addition to red and yellow is needed in caution/warning systems."

"The use of all colored lights in the cockpit should be standardized."

There were a few recommendations that another color, in addition to red and yellow, was needed to identify a third category of warning. While red and yellow in general refer to immediate action and deferred action items, some feel the third color would indicate that something is not quite correct but that no action is required. Such items are also often referred to as advisories. Any clear-cut rules for the use of these colors was not made apparent during the survey, and they appeared to be left largely to the individual contractor. Even the Air Force admitted that the military specifications should be revised with respect to definitive application of the various colors — red, yellow, blue, green, and white. Some recommendations were also made to the effect that a cautionary color in addition to aviation yellow should be introduced to differentiate between cautions that require no pilot action and those that require pilot action at a deferred time.

A similar concept is recognized by the SAE S-7 Committee, which is studying the need for a third level of warning as well as other colored lights in the cockpit, whether or not they relate directly to a warning system. Such a possible fourth level has an effect on the "darkened cockpit" concept discussed earlier.

Heretofore, colors like blue, green, and white have been used for advisories or to signify status of a system. This application appears to be growing, particularly with modular navigation and display units. It is apparent that both the civil and military favor some resolution of this problem, and concerted, coordinated action is needed to resolve these definitions and to identify the colors so used. Criteria should therefore be redefined for each of the colored lights used in the cockpit and should also apply to the use of light emitting diodes (LED). It was pointed out that technology is only now developing to provide colors other than red for LED's.

In addition to the colors already mentioned, there was a recommendation that, in taking a new look at the use of colors, attention should be directed to the use of combinations of red and blue as now used on many public safety vehicles. It was pointed out that an unidentified study at the University of Southern California indicated this to be an intolerable combination, one which is extremely annoying and therefore quite attention-getting. A second reason for considering this combination was the fact that many people are color-blind to red.

A limited number of red and yellow warning lights are used in general aviation aircraft. Colored lights have been considered ineffective for stall warning and therefore are being eliminated from these aircraft. An audible stall warning has been considered much more effective than a visual one. Cessna has found it necessary to add two more colors in order to differentiate the wheels up and down positions on a float plane. Here the normal red and green lights were insufficient because of the various combinations possible; therefore a blue light for gear-up and a brown-amber light for gear-down were added to identify when floats are installed. Most of the lights being added to these cockpits appear to be associated with information-type advisories related to navigation and system operation.

Guidelines with Mixed Reaction and Acceptance: General

1. "An improved c/w system for retrofit is desirable." There was mixed reaction as to the desirability of a retrofit system, and after completing the survey, it was concluded that there was a misunderstanding as to what was deemed to be retrofit. Retrofit could be interpreted as placing a revised system in existing airplanes flying today, or it could be interpreted as placing the revised system in existing aircraft models which are yet to be produced, thereby enabling the revised system to be incorporated at the factory. It appears that the latter would be entirely feasible, where there are very limited possibilities of doing so in existing aircraft. The strongest possibility in this regard, however, was noted to lie with the electronic voice generator which, if found acceptable, could be designed so that a single unit, tied into the necessary sensors, would be all that was needed to be added to the cockpit. Many of the questions discussed under voice warning would have to be resolved before such a system would be accepted. This potential for retrofit of a single electronic voice generator was considered encouraging enough to warrant considerable effort being expended to resolve these questions.

2. "Reverse the trend toward teaching pilots basic systems only (BSO), that is, procedures only without a thorough knowledge of the aircraft systems." This is really a question for airline training personnel, but it also involves basic concepts of aircraft systems design. It is probably not a subject for other than limited discussion here except that it was felt by some to foster a "dependence on warning devices" rather than on basic knowledge. It is of interest here because the increasing complexity of aircraft systems and cockpit information and controls are related to the c/w system used. The trend toward the use of on-board computers, electronic displays, and more automatic systems was also recognized by most of those interviewed. This problem will undoubtedly continue as an evolutionary development in which new designs and more automation must be reflected in revised training procedures, but a degree of iteration and swinging of the pendulum will probably continue. Whether basic systems only (BSO) aggravates or reduces the problem of c/w system design is beyond the scope of this paper. It is mentioned here because there were strong feelings among a number of those interviewed that this trend must be reversed and a return made to providing flight crews with a better understanding of their aircraft systems so that the handling of c/w indications does not become primarily a conditioned reflex.

Guidelines with Mixed Reaction and Acceptance: Visual

1. "A master warning light should be used." We first need to distinguish whether a master red warning light or a master-yellow caution light is being discussed. A master caution light is generally favored because of the fact that annunciator panels quite often are located in positions that are out of the pilot's direct visual cone. A single yellow light to serve the alerting purpose for cautionary indications is usually needed and is generally accepted for the cases where the annunciator panel is remotely located.

Examples were also found where a red central warning light was needed because all red warnings were located in a separate panel to the side of the main instrument panel. Their use also may be dependent on whether red warnings are grouped near the ADI and other flight instruments, in a panel separate from yellow caution lights, or whether they are mixed into the same central panel. Again, examples of each exist. If a trend could be determined, it would be in line with the earlier guideline to reduce the total number of red warnings to less than 10, thereby making it possible to separate them from the main cautionary annunciator panel. The need, however, by nature of red warning indications (immediate action) is to attempt to group them as close to the ADI as is physically possible. The result therefore is to cluster one master cautionary light with a variety of red warnings in this area.

Some recommendations were specific in stating that master warning panels and master warning lights ought to be replaced with a single alerting device. This device would be aural, visual, or both, and the c/w information displayed on a CRT on a priority basis, supplemented by written instruction to the pilot as to action to be taken. Other preferences were expressed by some for separate warning and caution panels.

2. "The annunciator panel should display only system malfunctions and not pilot errors." A similar recommendation was that there should be separation between cautions and warnings resulting from human failure and those resulting from system failures and that the crew should be able to distinguish clearly between them. There was no clear-cut method for accomplishing this, however. Some felt that audio warnings should be reserved for crew failure situations.

Another recommendation was that a master warning system should be confined to system malfunctions only. In such a system, a master warning light, centrally located for a pilot, alerts him to a c/w indication elsewhere. Several reasons for this interpretation were provided. First, any information related to aircraft control and navigation should be associated with the instruments being used for this purpose. It was emphasized that the use of isolated warning lights that are not directly associated with the control element or information affected by crew error or deviation cause distraction and introduce delays. One example of associating the warning information with the instrument being used was the case where the radar altimeter bug could be set to give a fly-up command when reaching decision height. This eliminated any reliance on audio tones or lights. Another example of this type of warning is the use of the flight path symbol in a terrain-following display which, in case of failure or excessive deviation below glide path, automatically gives the fly-up signal. The particular system in question also employs an adjoining red light affording a comparison between the two procedures. The former was clearly preferred, while the latter was considered distracting.

Carried to its ultimate conclusion, the desire to separate system malfunctions from pilot errors may be based on the desirability of obtaining significant improvements to the basic flight display of information so that the pilot has no need for auxiliary warning devices. Military experience with integrated displays (large head-up) employing integration of all information required for the particular task, including airspeed, altitude, flight path angle, velocity vector, and deviation information, has shown this is what is really needed. Until such improved displays are available, the opinion was expressed that we would continue to have conflict between providing sufficient warning and alerting devices and total distraction of the pilot from his primary task.

With a computer capability, it is possible to provide a written message pertaining to the warning in the integrated display, regardless of whether head-up or head-down. This was considered a desirable solution and would, of course, be applicable to any type of electronic attitude instrument.

3. "Flashing lights should be used in c/w systems."

"Flashing lights are excellent attention-getters but are seriously distracting." There was general agreement that flashing lights are, at the same time, excellent attention getters but seriously distracting. There was no agreement on how the undesirable characteristics could be minimized. For this reason, they have been received with mixed reaction. The use of flashing lights has also met with mixed reaction due to their excellent visual alerting capability, but this is modified by the tendency of pilots to cancel them immediately. The Civil Aviation Authority (CAA) of the United Kingdom favors the use of a flashing light for alerting of either a primary (red) or a secondary (yellow) warning. It is clear that the CAA prefers a flashing master warning light on both the captain's and first officer's panel. On the master warning system panel, the CAA also feels that flashing lights are desirable because they can continue to flash without becoming as annoying as an audio signal. Further, they can be detected by peripheral vision. The French, however, favor an audio tone for alerting, so on joint aircraft programs an audio is added for primary warning. The airlines object to using the same flashing concept for both red and amber lights, so the concept of neither red nor amber flashing on the master warning system panel has been adopted. The military does not favor the use of flashing lights, but numerous waivers have been granted for their use in specific cases. The Air Force feeling is that flashing lights are generally too distracting and tend to restrict their use.

Additional work is obviously needed to determine if, when, or where flashing lights should be used. One solution suggested was to automatically limit the flashing phase, after which the light reverts to a steady mode. It has also been suggested that the use of intermittent flashing lights, which remain on for 10 sec and then go off automatically, on a central warning panel could eliminate the need for the master caution or warning light. On one recent aircraft, which uses several red-labeled warning lights near the ADI, plus a master caution (yellow) relating to the annunciator panel located elsewhere, the master caution light flashes until it is pushed to cancel, whereas each red light, which is labeled, is steady. Note that in this case the pilot and copilot are each furnished with all of these. Some other manufacturers, including those in general aviation, also use the concept of the master caution coming on flashing with the ability to be punched out. The fault still remains lighted on the annunciator panel.

The application on one GPWS was the initial use of a steady red light which changes to flashing later. This appears to follow the concept of providing an advisory first and then a command but is counter to the concept of flashing for alerting.

One concern expressed about the use of flashing lights, at least in the spacecraft application, is that they are extremely costly in terms of software. They are specifically used in presentation of information on a CRT as a means of drawing attention to specific information in a complex display.

Pilots observed that, when faced with a flashing light, there is a strong reaction to cancel the light even before they know what it means. Whether a flashing light can at the same time be a good alerting device and yet not cause serious distraction is not clear because the effects appear to be somewhat contradictory. However, the ability to cancel a flashing light removes some of the distraction. One concept is that if a flashing light is adopted, it should be first in the flashing mode, thereby fulfilling its alerting function, and then go steady after initial action is taken, if this is what is desired. Some cases were found to exist wherein the light came on steady and then moved into a flashing mode. The option to cancel a flashing light was considered almost as important as the ability to cancel an audio signal.

A second method of reducing the disturbing distraction of the continuous flashing light is to automatically limit its flashing cycle. This, of course, assumes that it will have accomplished its alerting purpose during the initial cycle. When both an audio and visual alerting means are used, automatic control of the flashing cycle may be entirely adequate. Like audio warnings, it was emphasized that flashing lights need to be kept to a minimum. Several examples were noted wherein the concept of flashing first and steady second were violated. The flashing red light is sometimes used for an engine overheat condition with a steady red for a fire. It was noted that the latter is more serious and requires faster response. One solution on another aircraft was to separate the two lights and make them both steady, using other means to alert.

On an L-1011 aircraft, operated by a foreign carrier, both the pilot and copilot have a master warning light which flashes until the fault is corrected. On one recent military aircraft, the master warning is a steady light, whereas the master caution flashes until it is pushed to cancel, leaving an annunciator light flashing on the central panel. One recommendation was to use a flashing light on the central panel for alerting, with automatic cancellation after 10 sec; this process could eliminate the need for a master warning light.

The flashing light is also sometimes used to indicate a transient condition, with a steady light referring to a steady condition. This led to the recommendation that the use of flashing lights needs to be standardized.

That flash rate can be important was illustrated by military pilots interviewed who had experience with two different recent aircraft, each of which used a flashing light on the annunciator panel to indicate the most recent caution or warning. On one the flash rate was high, while on the other it was slower. The slower was strongly recommended as much easier to read. As information on the actual flash rates was not available, it must be assumed that the rates were within those specified by military standards. In any case, it suggests that improved criteria with respect to human factors in relation to the best range of flash rates appear to be needed.

Guidelines with Mixed Reaction and Acceptance: Tactile

1. "The use of tactile warnings should be extended in order to diversify the inputs to the pilot." This is a controversial area in which there exists a wide difference of opinion. There does appear to be some current effort, evolving partly under military sponsorship, to investigate extended use of tactile warnings in order to reduce reliance on audio and visual cues. There also exists the opposing viewpoint that, with the exception of the stick-shaker, there is little interest in extending the use of tactile warnings. They are, in general, the least reliable because a pilot is not always able to discriminate their meaning.

At least two companies, however, indicated an interest in the expanded use of tactile warnings and referred to work being conducted at Ohio State University with a control stick grip that makes use of tactile inputs to the pilot, and to Air Force interest in the application of body pressure through segmented pneumatic seat and back cushions.

One of the desirable aspects of the stick-shaker is the fact that it relates directly to the control involved in exercising corrective action. It might be expected, therefore. that tactile devices not related to the control involved or a clearly identifiable hazard may not find ready acceptance.

ANALYSIS AND COMMENT

In the preceding section, the discussion was almost exclusively confined to the observations made by respondents during the survey. In this section the information is summarized, along with comments and analysis of the writer, in order to develop the primary conclusions that have evolved from the study.

Less commentary is required for those guidelines and philosophies for which there was general acceptance, while more attention is devoted to controversial areas. Finally, a list of recommendations for investigation or research by NASA is provided, representing the opinions of both the respondents and the writer.

General

There appears to be validity in the conclusion that an excessive number of individual warning signals is presently provided in many transport and military aircraft. Fairly unanimous recommendations that immediate action warnings be reduced, that auditory signals be confined to four or five, and that the large numbers and complex arrangements of caution/warning lights be simplified and improved, certainly bear witness to this fact. The proliferation of warning sounds and lights, all competing for pilots' attention and prime instrument panel space in the pilots' central cone of vision is cited as compelling evidence of the need for reevaluation of the situation. Considerable attention is therefore justified to studies of some of these basic questions in order to improve the guidelines for future designs and to correct design errors that appear to have been made in the past. A promising solution for reducing the large numbers of warnings which could occur at any given time lies in the use of some method for prioritizing and inhibiting warnings by phase of flight.

The arguments for inhibiting and prioritizing warnings lie in the potential for reducing some crew overload conditions, and allowing faults or errors to be handled one at a time in a systematic manner according to a predetermined priority. Theoretically, this should lead to a decrease in reaction time and to a reduced likelihood of inappropriate corrective action.

Risks are foreseen by some in not providing all warnings or caution indications immediately as they arise. One argument is that we are not intelligent enough to anticipate correctly the wisest priorities for all possible combinations of possible warnings. The counter argument may be that, if this is the case, we cannot expect a crew to resolve the same question any better within seconds while under the pressures of the operational situation. Another argument against prioritization lies in the fact that each type of aircraft is a unique design and no single system for prioritizing will be possible; it will vary among aircraft.

Advanced technology can contribute effectively to the solution. Positive steps in this direction are reflected in current design trends involving increased automation, digital computers, and electronic displays in which information can be integrated and displayed in a variety of ways.

It is possible also that the requirements for many of today's warnings might be eliminated and a better solution provided by redesign of the cockpit information display system for normal operations; here, too, currently available computer and display technology could be utilized effectively. We must recognize, however, that such redesign will progress rather slowly in actual application to transport aircraft and most likely will not be incorporated as retrofit in existing models. In addition, potential for improvement exists from better application of human factors doctrines in defining, not only what information is present, but also how it is best presented.

Work in this area should deal, not only with the details of the c/w system, but also with other elements of the total operational situation. The failure of flight crews to heed obvious warnings signals, of which there are numerous examples, appears to be attributable, in significant measure, to the frequent high level of cockpit workload. In such an environment, the number of extra tasks that can be handled at a given time is reduced, and this affects adversely the crew's ability to recognize and respond to information not relating directly to the cause of the high workload. Obviously, the factors contributing to high workload need to be identified and reduced or eliminated to enable c/w systems to retain their effectiveness.

One additional factor that merits consideration as a contributor to the general problem is that of the fundamental training concept identified as "Basic Systems Only." A growing trend toward teaching "BSO" is believed by some to encourage pilots to become undesirably warning dependent. Obviously, the complexity of modern electro-mechanical-hydraulic systems makes it impractical for flight crews to attempt to understand and retain minute details of design, function, and performance. It is essential, however, that they have sufficient knowledge to operate such systems with safety and efficiency. How far the training of flight crews should go toward providing a limited understanding of these complex systems is a gray area which must be explored carefully. While there may be some basis for human factors studies of this problem, it is considered primarily a subject for manufacturers and airline training organizations and personnel and not one of high priority for NASA study.

Reduce Number and Types of Warnings

Reduction in the complexity of warning systems, as evidenced by the large numbers of both audio and visual indications, was the particular need most frequently mentioned. Emphasis here should be on reducing the number of immediate action warnings and the number of auditory signals. An effective improvement method that deserves immediate attention would be to inhibit unnecessary warnings on the basis of flight phase and to establish a prioritizing systems for those retained. It is necessary, however, to accept the fact that the pilot must remain in a position to make final decisions regarding priorities; this poses the need to provide him with sufficient information on simultaneous problems to enable him to evaluate the overall situation properly.

In addition, it is important that some means be provided for cancellation of warnings after they have served their primary purpose. Manual cancellation by the pilot is only one means that could be used. As one of the human factors elements that could be studied in this area, consideration should be given to automatic cancellation or to intermittent warnings which allow periods of respite from the alerting distraction.

One concept which appears to have merit is that, after cancellation of the central warning, whether red or amber, the fault information be retained on an auxiliary panel until corrected. The use of a flashing mode on the auxiliary panel until the fault is corrected has some merit in cases where numerous fault indicators remain lighted on a given flight. In the case of alpha-numeric message displays, where emphasis is on readability of only one or two messages, some method for storage and display of multiple faults must be devised. Possible methods include the use of a single symbol at the end of the message or a recall capability wherein all existing faults may be reactivated in the display, either sequentially as they occurred or on a prioritized basis. The method used may depend on whether the alpha-numeric message line or a CRT is employed. Determination of the best application of each should be made early in the investigation.

Direct vs Indirect Cues

The use of direct cues, that is, of those that provide information about corrective action, has been shown to reduce pilot reaction time by as much as 6 to 9 sec. While the value of reduced reaction time is obvious, there does not seem to be sufficient evidence at this time to establish that the means used for alerting the pilot can or should always be a direct cue. The potential value of direct cues over indirect ones, regardless of whether they are auditory, visual, or tactile, appears to be great, however. The direct cues which appear to provide the greatest potential are spoken or written messages, labeled lights, digital computer messages displayed on a CRT or LED type display, and the stick-shaker.

There is considerable interest in and arguments for the use of audio tones only for alerting purposes and possibly to convey the proper level of warning. This would greatly simplify the use of warning sounds and enable more rapid standardization once an acceptable means for providing one or more direct cues is available in the cockpit. One argument against this procedure is that an alerting method that does not provide a direct cue, that is, unmistakable information on which the crew can act, results in unnecessary delay.

In terms of possible retrofit and requiring the least redesign or space requirements on the instrument panel, the most promising methods available to improving the direct cues are voice and the alpha-numeric message display.

Auditory

There is general consensus that the use of voice cues through verbalized messages appears to be the direct auditory cue that provides the greatest potential for payoff in future c/w systems. For this reason, it should be given the highest priority in any research and development efforts. In general, auditory signals have been considered, due to their compelling nature, to be reserved for pilot failure modes or for a few critical conditions or failures requiring immediate action or decision by the crew. It appears possible that the use of verbalized messages could be more widespread if the potential for conflict with other communications could be minimized. In other words, voice messages could also provide an alternative to reading a visual message for lower level warnings which do not require immediate action or can be recalled at a time when the crew is not overloaded. While much study has been given to the use of voice as to terminology, message content, and other characteristics, very little research has been conducted within the constraints of the operational situation, either simulated or real. Future work should not only reconsider questions of the message format and treatment of urgency level under simulated operational conditions, but should do so both in prioritized and non-prioritized systems, incorporating multiple failures, and in conjunction with an integrated but separate visual warning system.

There was a clear indication that pilots prefer advisory information to commands from voice warning. It is not clear yet how far this guideline should be carried in the design of voice warning systems, but such psychological aspects which affect individual response must be taken into account. If we accept the philosophy that the final decision is made by the on-board captain and crew, the issuance of "voice commands" by electromechanical means is a contrary philosophy. If commands are treated as advisory, with perhaps a level of urgency provided, the basic philosophy remains intact. A comparison may also be made with the flight director which is often referred to as a command instrument. If a pilot responds to every movement of a flight director, his attention becomes so intense on this one bit of information that his visual scan of other information is interrupted, his workload goes up, and he becomes a slave to this one source of information. If, on the other hand, he treats the flight director as a quickened bit of advisory information, he still achieves satisfactory performance without losing the scan pattern necessary to maintain situation awareness.

Visual

Although a well organized, systematized use of labeled lights has been recognized as reasonable and acceptable, there are characteristics even here which appear to warrant improvement. The question of readability under operational conditions, stemming from relative size of the lettering or cockpit lighting conditions, needs to be reconsidered in their design. Specific attention should be directed to the question of readability and clarity of visual messages under adverse lighting and vibration or turbulent conditions. While there is the potential of providing great detail in visual messages through computer displays, this must be balanced by the need for conciseness and readability. Specific new technology which should be evaluated includes the digital computer in conjunction with the concise message readout versus the total CRT display. It is possible that both have a best application and may not be competitive in that sense.

The use of flashing lights and flashing display elements is in need of a basic philosophy and guidelines for their use. The conflict regarding their use arises from the fact that they are at the same time an excellent means of attracting attention and that they may very easily become highly distracting. Some of the answer may lie in limiting the flashing period and using flashing lights only for alerting purposes, or perhaps as a means of identifying a level of urgency. On the other hand, the use of flashing yellow lights, as on an annunciator panel, appears to provide an excellent method of indicating that a fault remains uncorrected, while permitting the cancellation of a central warning. The use of a flashing mode in display elements to indicate unreliable information has apparent merit, but the concept must be reconciled with the use of flashing lights in warning systems. The common parameter in each, however, appears to be that of drawing attention.

Multiple Cues

This leads to the question of multiple cues. In order to ensure that a warning is not overlooked, experience suggests that there is merit in providing multiple channels of information, that is, auditory, plus visual, or either of these plus tactile. While evidence to date indicates that multiple channels are required to ensure that pilots under high workload conditions have an increased capability for recognizing and responding to a warning, the possibility exists, with verbalized, digitized and printed CRT message concepts, for providing significant improvements in information content. These, plus improvements in the concepts for alerting the pilot, may make it possible to reduce such duplication and still achieve satisfactory results. Such a consideration should at least be a potential goal for any research and development program. Recommendations have been made that auditory signals be reserved for alerting purposes and visual signals be used for action, but there does not appear to be sufficient evidence at this time to warrant such a broad concept.

Uniform Standards and Guidelines

The strong plea made by respondents for improved standards and guidelines for warning systems is seen as an indication of their importance. It was evident that the military standards have been an important source of whatever standardization exists today. Their usefulness extends also to civil aviation where they can be used as guidelines without the effect of becoming requirements.

In this regard, NASA should work closely with the FAA, and with Boeing, who is conducting studies under FAA sponsorship, to identify and provide support for updating those standards in need of updating. This will tend to ensure that NASA research is conducted in a manner and within a time frame that will provide maximum application and hence the greatest return in terms of improvements in cockpit warning systems.

Standards under development by the SAE S-7 Committee can provide an important step in this direction, largely because they will not have the effect of regulations, thereby enabling achievement of standardization by consensus and agreement without discouraging development. Despite the indicated value of the military standards, even the military agree they require updating and improving. During the survey only a few of the conflicts within the military standards were identified. An effort should be made to review these standards in detail, identifying all areas where change may be required, and a singular effort established to update them. Some form of coordination with the SAE S-7 Committee in this regard would seem desirable.

One of the first places to begin standardization is in the terminology being used. This is currently a subject under study by the S-7 Committee. It is important for NASA to keep abreast of these developments so that current, revised, and approved terminology is used throughout any research and development program.

Additional specific areas where new guidelines are needed in order to enhance future development are redefinition of categories or levels of warnings and the standardization of a few auditory signals which may be used either as alerting tones, with or without verbalized message, or as the few standard warnings that are universally applied to a few items, such as landing gear and fire. Improved guidelines are also needed to clarify the use of flashing lights in c/w systems, as is redefinition of the use of colored lights in order to retain the concept of a dark cockpit during normal operation.

Reliability

It has been shown that reliability is a significant determinant of the effectiveness of c/w systems. A c/w system is equally unreliable whether it malfunctions — to produce false fire warnings — or whether it is so designed or adjusted, with respect to limits, that it produces repeated nuisance warnings. An unfortunate illustration of the latter problem is afforded by the recent accelerated introduction of the GPWS into operational service without adequate preparation and evaluation. While remarkable progress has been made in achieving a high level of reliability with avionics systems, still more progress must be made if warning systems are to be accepted and used effectively by flight crews.

Experimental studies involving new technology are, of course, very important, but they should not be conducted at the expense of comparative studies involving labeled lights and auditory signals, with and without verbalized warnings. Improved guidelines and recommendations for the application of these systems may be significant in improving current cockpits.

Evaluation Procedures

Perhaps the greatest deficiency in the past implementation of cockpit warning system has been a lack of objective evaluation under realistic operational conditions. Such an evaluation can be accomplished most expeditiously by using current advanced training simulators and full mission simulation techniques. Such programs are expensive, require a broad effort to implement, and require extensive data recording and reduction efforts. For these reasons, such full mission evaluation studies should probably be confined to the final evaluation phase of either new designs or comparative studies. They should be preceded by systematic experimental studies, beginning with simple laboratory experiments to separate the large number of variables or concepts possible and to understand the important differences between alerting and informing for decision.

This focuses attention on the desirability of looking at c/w systems as very general in nature, incorporating not only the immediate action warning, but also the deferred or nonaction transfer of information to the pilot and crew, such as caution, advisories, and status indicators. These, then, relate to categories or levels of warnings based upon criticality or response required. Another aspect of importance appears to be the separation of the alerting function from the information part of the warning message. There could be value in considering a warning in terms of alerting, informing of the problem, and information relative to decision and action. It is suggested that the requirements of these three phases may differ. Is the use of a direct cue, for example, expected to accomplish all three? Or is alerting a separate function which might more clearly provide an alert if separated from the need to inform and generation of decision and action. Perhaps further experimental studies will be required to provide answers to these questions and to the desirability of adhering to a current military standards that require any warning to be preceded by an alerting signal or tone. Military standards also explicitly require a nonverbal signal to precede a verbal warning.

Studies involving basic human factors and specific warning systems should consider those standards already outlined in the Mil. Stds. 411 and 1472 for specific confirmation or rejection of existing information.

The next phase should be part-task simulation studies which involve combinations of the basic elements of cockpit warning systems for which a more refined comparison or evaluation is required. These will provide insight into the secondary advantages or disadvantages of specific elements but would not be expected to provide valid reaction times nor comprehension under realistic or high workload conditions.

The fundamental performance measure in investigations of c/w systems is the pilot reaction time for proper response; this obviously involves considerations of comprehensibility and proper interpretation. Research data appear to be needed in order to define more authentic and realistic reaction times to warnings, particularly in the context of the total operational environment. A controversy over what should be accepted as minimum response time may be related to the latter factor: 1 sec is recognized by the FAA, the CAA says 2 sec, and various pilot groups say it should be more like 6 to 7 sec. This question obviously warrants study.

A review of the problems and recommendations obtained during this survey should provide a basis for research and development progressing from (1) specific elementary experiments to (2) part-task simulations involving more complete systems, and (3) a full mission simulation study involving two or more basic systems composed of subsystems selected from the results of (2). This is illustrated in table 4.

TABLE 4.- EXAMPLE OF SYSTEMATIC INVESTIGATION OF COCKPIT WARNING SYSTEMS CONCEPTS

Specific laboratory experiments or studies involving c/w systems elements	Part-task simulation studies involving c/w subsystems with important cockpit environment	Full mission simulation studies to evaluate and compare complete c/w systems composed of most promising subsystems
What are 5 best auditory signals? Should auditory signals be confined to immediate action? Should auditory signals, including voice, incorporate urgency? How?	Part Task Simulation I Scenario designed to evaluate experimental results	Full Mission Simulation Scenario designed to evaluate tentative conclusions from Part Task Simulator Evaluations I and II and additional scenario content in footnote.
Should alerting signal be used with voice? Should alerting signal, if used, be continuous, push to cancel, or auto-cancel? What standards are desired for voice warning message context? What are best methods for indicating multiple warnings and prioritizing for single voice generators?	Part Task Simulation II Scenario designed to evaluate experimental results	

Note: Also included in full mission scenarios would be results from similar systematic investigation of labeled lights, visual message display, CRT applications, etc.

RECOMMENDATIONS

Each visit was concluded with a request for specific recommendations for investigation or research pertaining to warning and alerting. In this section are listed the primary recommendations received, some of which were specifically designated for NASA action.

General

1. NASA simulation data and support is needed on c/w systems.

    - NASA should be concerned with concepts only and not specific designs.

    - NASA effort should concentrate on providing data to guide and assist industry in the design of c/w systems.

2. The need for new equipment pertaining to c/w systems should be confirmed by ensuring that it will accomplish its desired task before making it a requirement.

3. NASA should provide objective evaluation of cockpit systems, including c/w, and should utilize full mission simulation in comparative testing of warning system concepts.

4. NASA should provide basic human factors data for use by industry (e.g., realistic reaction times, acceleration thresholds, types of alarms, etc.). This should include determination of what functions a flashing light, bell, audio tones, and voice are best used for. It should also include an evaluation of methods for indicating the level of warning.

5. The adequacy of methods by which pilots and copilots monitor each other should be determined. The relative merits of automatic monitoring and pilot monitoring should be determined.

6. Methods for cancelling both red and yellow master warning lights and warning tone or voice messages should be evaluated.

Auditory

1. Develop and evaluate the use of voice warning in c/w systems, including the use of a single voice generator

2. Conduct evaluations of voice warning in conjunction with a visual master warning panel system

3. Develop and evaluate a standardized voice warning system for inclusion in all aircraft; supplement this with a master c/w panel system as on the B-1

4. Evaluate the use of modulated versus flat tone voice warning as well as methods for conveying a sense of urgency

5. Investigate the removal of the annunciator panel from prime panel space by supplementing with voice

6. Develop and evaluate standardized tones and guidelines for landing gear warning

7. Determine and evaluate a single master warning sound to alert for all critical items

8. Determine five best audio sounds for basic standard auditory signals

    - Determine if these auditory signals should be limited to potentially catastrophic or most urgent situations only

    - Determine if these auditory signals should be reserved for crew failure only

Visual

1. Criteria should be redefined for what constitutes red, yellow, blue, green, or white light and for the use of LED colored lights.

2. Investigate whether a third color is needed in addition to red and yellow for warnings and cautions.

3. Brightness, contrast, and visibility of visual c/w elements should be investigated under a variety of cockpit lighting and vibration conditions.

4. Visual warning systems need to be evaluated under conditions of high ambient light due to fog in low visibility approaches.

5. Evaluate techniques for determining brightness, contrast, and color compliance with specifications.

6. Investigate the use of flashing lights and determine the best application in a c/w system. Resolve existing conflicts in their use.

7. Investigate the use of a condensed alpha-numeric word display in conjunction with voice warning and contrast with a CRT display plus voice.

8. Investigate best ways of displaying c/w information on a CRT.

   - For systems information and checklists
   - For automated checklists
   - Other applications

9. CRT use should be investigated for display of warning information on a priority basis, with written instructions on action to be taken.

Tactile

1. More tactile warnings should be developed and evaluated.

Multiple Cues

1. NASA should investigate and demonstrate the complementary use of voice warning and alerting with a visual system incorporating first, an alpha-numeric message readout, then with a standard labeled light system, then with a CRT display.

2. A need exists for development of the logic for prioritizing c/w information and for redundancy requirements. Investigate and resolve methods for prioritizing messages.

3. Kinds and number of warnings that a pilot can prioritize should be determined, as should information on how pilots do prioritize information received.

4. NASA should conduct studies to enable a change in Federal Aviation Rules against prioritizing of c/w signals.

5. Methods should be developed and evaluated for incorporating or relating the control involved with each urgent warning.

6. The use of auditory signals, including voice, should be evaluated against a visual system to determine effectiveness or deficiencies under conditions of high workload.

Uniform Standards and Guidelines

1. Mil. Stds. 1472 and 411 need revising, with emphasis on rationale behind them.

2. Standards and guidelines for c/w system design are needed for transport aircraft. A needed revision of SAE 450C, "Visual, Audible and Tactile Signals on the Flight Deck," is in progress.

New Warning Systems

1. The need for attitude warning should be determined.

2. A computerized system is needed which makes the potential of collision evident only when there is high probability of collision.

3. A method is needed for integrating the GPWS or other add-on c/w items such as turbulence, wind shear, collision potential, or attitude into a central warning system.

REFERENCES

1. Batemen, C. D.: Introduction of the Ground Proximity Warning System (GPWS) into Airline Service. Sundstrand Data Control, Redmond, Washington. Paper presented at 29th International Air Safety Seminar, Flight Safety Foundation, Inc., October 25-29, 1976, Anaheim, California.

2. MIL-STD-1472B: Human Engineering Design Criteria for Military Systems, Equipment and Facilities. 31 Dec. 1974; superseding MIL-STD-1472A, 15 May 1970. Department of Defense, FSC-MISC.

3. MIL-STD-411D: Aircrew Station Signals, 30 June 1976; superseding MIL-STD-411C, 21 August 1967, FSC 1500.

4. Smith, Wayne D., et al.: Independent Altitude Monitor Alert Methods and Modes Study, Report FAA-RD-75-86, July 1975, Boeing Commercial Airplane Co., Seattle, Washington; prepared for U. S. Dept. of Transportation, Federal Aviation Administration, Systems Research & Development Service, Washington, D.C.

5. Society of Automotive Engineers Standard 450 C: Visual, Audible and Tactile Signals on the Flight Deck.

6. Vanderschraaf, Abe: Problem Area: Warning Systems, Fokker-VFW B.V., paper presented at 29th International Air Safety Seminar, Flight Safety Foundation, Inc., October 25-29, 1976, Anaheim, California.

BIBLIOGRAPHY

This report is based primarily upon the information obtained during visits to 22 aviation organizations. The result of these visits were summarized in separate trip reports which comprise the primary source material for this report. (Items 1-22) While much additional work has been done on the subject of c/w systems and a bibliography of additional reference material was developed, it was considered too detailed for inclusion with this report and not pertinent to the specific objective of obtaining first-hand information from the industry.

Trip Reports Relative to Aircraft Warning and Alerting Systems:

1. Visit to Boeing Airplane Co., Seattle, Washington, October 18, 1975.
2. Visit to VFW Fokker, Schiphol Airport, Amsterdam, The Netherlands, November 6, 7, 1975.
3. Visit to Aerospatiale, Toulouse, France, November 14, 1975.
4. Visit to the Civil Aviation Authority, Redhill, England, November 20, 1975.
5. Visit to the British Aircraft Corporation, Flight Test Department, Fairford, England, November 21, 1975.
6. Visit to Rockwell International, Los Angeles International Airport, El Segundo, California, March 3, 1976.
7. Visit to Lockheed California Company, Burbank, California, March 4, 1976.
8. Visit to McDonnell-Douglas, Long Beach, California, March 4, 1976.
9. Visit to McDonnell-Douglas, St. Louis, Missouri, March 23, 1976.
10. Visit to Wright-Patterson Air Force Base, Dayton, Ohio, March 24, 25, 1976.
11. Visit to the Navy Safety Center, NAS, Norfolk, Virginia, April 5, 1976.
12. Visit to meeting of the SAE S-7 Committee, Washington Hilton Hotel, Washington, D. C., April 6, 7, 1976.
13. Visit to FAA Headquarters, Washington, D. C., April 8, 1976.
14. Visit to the Grumman Aerospace Company, New York, April 9, 1976.
15. Visit to Joint Test Force for the B-1, Edwards Air Force Base, California, May 13, 1976.

16. Visit to USAF Directorate of Aerospace Safety, Norton Air Force Base, California, May 14, 1976.

17. Visit to Sperry Flight Systems, Phoenix, Arizona, May 17, 1976.

18. Visit to Cessna Aircraft Co., Wichita, Kansas, May 25, 1976.

19. Visit to Beech Aircraft Co., Wichita, Kansas, May 25, 1976.

20. Visit to General Dynamics Corporation, Fort Worth, Texas, May 26, 1976.

21. Visit to NASA, Johnson Spacecraft Center, Houston, Texas, May 27, 1976.

22. Visit to NASA, Ames Research Center, Moffett Field, California, June 1976.