LESSONS LEARNED FROM PILOT ERRORS USING AUTOMATED SYSTEMS IN ADVANCED TECHNOLOGY AIRCRAFT

William R. Nelson, James C. Byers, Lon N. Haney, Lee T. Ostrom, and Wendy J. Reece
Idaho National Engineering Laboratory
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415
(208) 526-0575

ABSTRACT

The National Aeronautics and Space Administration (NASA) sponsored a project at the Idaho National Engineering Laboratory (INEL) to investigate pilot errors that occur during interaction with automated systems in advanced technology ("glass cockpit") aircraft. In particular, we investigated the causes and potential corrective measures for pilot errors that resulted in altitude deviation incidents (i.e. failure to capture or maintain the altitude assigned by air traffic control). To do this, we analyzed altitude deviation events that have been reported in the Aviation Safety Reporting System (ASRS), NASA's data base of incidents self-reported by pilots and air traffic controllers. We developed models of the pilot tasks that are performed to capture and maintain altitude. Two types of models were developed to provide complementary perspectives of these tasks: sequential models and functional models. Both types of models show the errors that occur in actual altitude deviation events in advanced technology aircraft. Then, errors from the ASRS data base were categorized according to the models, to help understand the potential causes of the different error types. This paper summarizes the methodology used to analyze pilot errors, the lessons learned from the study of altitude deviation errors, and the application of these results for the introduction of advanced technology in nuclear power plants.

I. BACKGROUND

It is often assumed the introduction of advanced computer-based systems into the operating environment will decrease operator workload and reduce the frequency of errors. This viewpoint is used to justify the introduction of new technology into reactor control rooms, without detailed thought about the effects of automated systems on operator roles and performance. Introduction of automated systems using such a "technology-centered" philosophy brings with it the risk of unexpected new opportunities for error. Before the nuclear industry implements increased automation in new reactor designs, it would be beneficial to look at the lessons learned in other applications, and to use this experience to develop a philosophy of "human-centered automation" for the nuclear industry.

The industry with the longest experience in automated systems is commercial aviation. Beginning with the introduction of autopilots in the 1930's to today's CRT-based "glass cockpit" aircraft with Flight Management Systems (FMSs) that can automate essentially all phases of flight, the aviation industry has a large experience base that the nuclear industry can benefit from. Advanced technology in the cockpit has, for the most part, increased pilot efficiency and reduced workload, however, some unexpected results have been observed. It has been found that the primary reduction in workload occurs during periods when workload is already low (e.g., during long periods of cruise), but that workload can actually increase during busy times (e.g., when the landing clearance is changed during descent into a busy terminal control area). In addition, entirely new types of error have been introduced. A significant number of errors have been observed because the pilot does not fully understand how the automated systems function during all modes of operation. Because of these unexpected effects of automated systems on pilot performance, there is a substantial interest in investigating the causes of these new types of error. Some studies have already been conducted. Sarter and Woods performed a study of pilot experiences and opinions regarding the advanced systems available in the cockpit.[1] They found that many pilots do not understand the logic and algorithms that underlie the automation, and hence cannot always anticipate what the automation will do, and are sometimes surprised by mode transitions they do not expect. Pilots have also expressed the concern of not understanding the effects of a partial failure of the flight management system.

The systematic identification and assessment of human errors has been practiced in the nuclear power industry for the past twenty years or so, and has received increased attention since the accident at the Three Mile Island (TMI) nuclear power plant in 1979. The National Aeronautics and Space Administration (NASA) commissioned a study at the Idaho National Engineering Laboratory (INEL) to investigate the applicability of methods of human error analysis and human reliability analysis, as used in the nuclear power industry, to the study of altitude deviation errors that occur in "glass cockpit" aircraft. This paper describes how these methods were used to analyze pilot errors, the results of the analysis, and potential applications of the lessons learned to the nuclear industry.

II. METHOD

A. Development of Task Models.

Models of the tasks that are performed to capture and maintain altitude in "glass cockpit" aircraft were developed. In order to provide a more complete picture of altitude deviation errors, two complementary perspectives were used, based on different approaches to the modeling of human error. The first, called the sequential model, was designed to show the prescribed sequence of actions involved in altitude maintenance, and the points at which errors can occur. The technique we used to show the sequential modeling perspective was the HRA event tree, originally developed as part of the THERP method.[2] The HRA models developed for this study were based on a relatively high level task analysis provided by NASA Ames. Two types of representational modeling, 1) a probabilistic risk assessment (PRA) event tree and, 2) the related HRA event trees, were incorporated in this analysis. The PRA event tree depicts a series of human actions and hardware events involved in altitude deviation scenarios. The HRA event trees depict the identified human actions decomposed into their critical subtasks.

The PRA event tree is presented in Figure 1. High level descriptions of the human actions and hardware events depicted on the tree are provided in Tables 1 and 2. The tree depicts twenty-six scenarios representing the possible successes or failures of each action and event. Each human action appearing in the PRA event tree and described at a high level in Table 1 was further depicted in an HRA event tree. An example HRA event tree is presented in Figure 2 .

A functional model provided a complementary perspective. The functional model is a hierarchical structure that starts at the top with an overall objective (for this project the overall objective was to safely complete a flight to a prescribed destination), the critical functions that must be performed to reach the objective, the tasks and subtasks that contribute to the performance of the critical functions, and the resource options (e.g. hardware systems) that are available to the crew for performing the tasks. The kind of hierarchical structures used in this study are called response trees because they graphically display the range of responses that are available to the crew for responding to challenges to the critical functions.[3] Modern transport aircraft are designed so that there is more than one way to perform many of the critical functions, so that safety can be maintained even if certain component failures occur. The different methods for maintaining each critical function are referred to as success paths. Response trees can be exercised manually or by computer to show the effects of different combinations of hardware or human failures, and the options or success paths that remain available to the flight crew for coping with the situation.

The top level functional model that was developed for this project is shown in Figure 3. This model of flight includes six functions: Takeoff, Flight Control, Monitor Flight Conditions, Navigation Planning, Monitor Navigation Process, and Landing. Each of these are broken down into tasks, and the tasks are further broken down into subtasks and the resources needed to perform each of the tasks and/or subtasks.

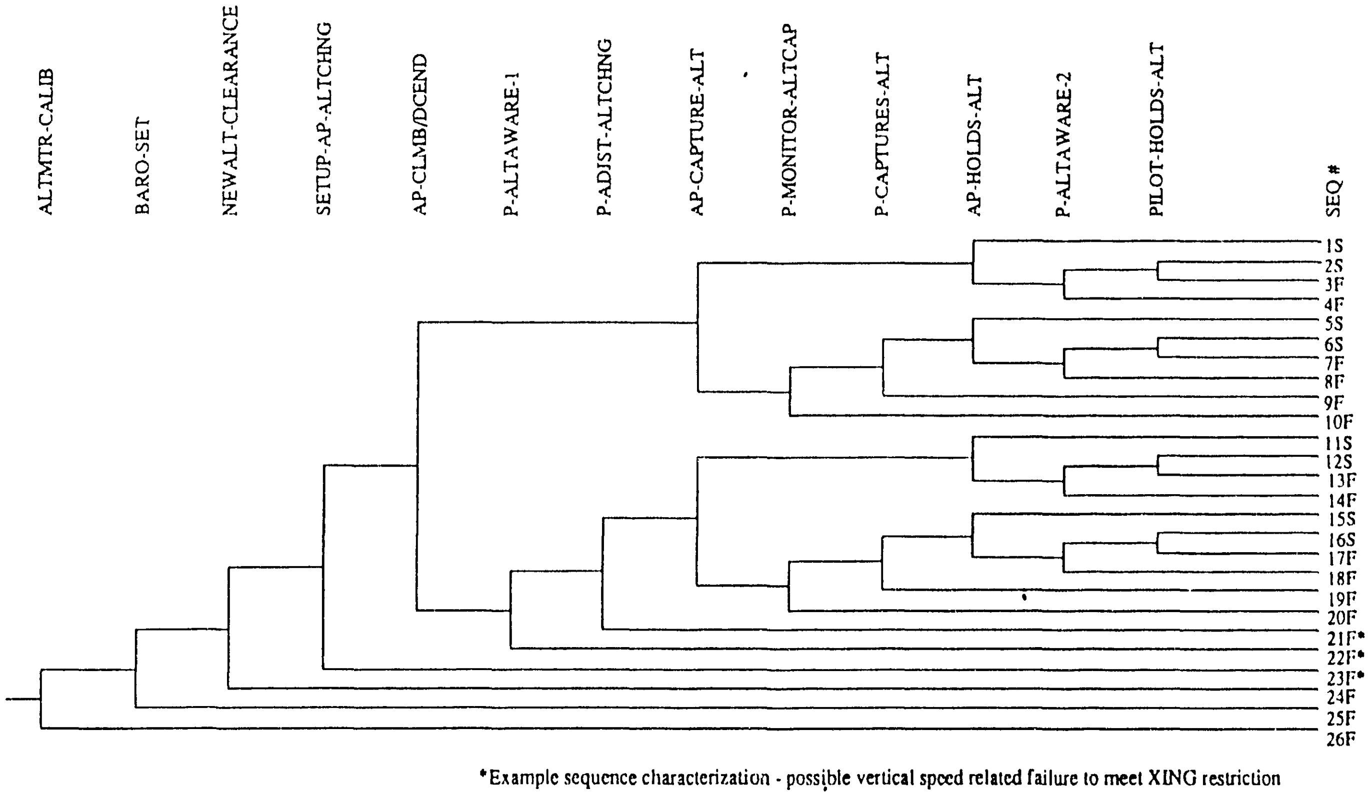

Figure 1. Altitude Deviation Event Tree

Table 1. Human Actions on Altitude Deviation Event Tree

ALTMTR-CALIB	Flight crew checks and notes altimeter discrepancies before takeoff.
BARO-SET	Proper reference barometric pressure obtained and set by flight crew
NEWALT-CLEARANCE	Flight crew receives new altitude clearance (includes XING Restrictions)
SETUP-AP-ALTCHNG	Flight crew properly programs and engages Auto Pilot (AP) for altitude change and capture.
P-ALTAWARE-1	Flight crew monitors altitude change in terms of clearance and any crossing restrictions
P-ADJST-ALTCHNG	Flight crew reprograms AP, or disengages AP and flies climb/descent to meet clearance and crossing restrictions.
P-MONITOR-ALTCAP	Flight crew monitors approaching capture altitude and altitude capture by the AP.
P-CAPTURES-ALT	Flight crew disengages AP and flies altitude capture.
P-ALTAWARE-2	Flight crew monitors hold altitude and maintains vigilance for deviation warnings.
PILOT-HOLDS-ALT	Flight crew reprograms AP, or disengages AP and flies, to hold altitude.

Table 2. Hardware Events on Altitude Deviation Event Tree

AP-CLIMB/DESCEND	AP climbs/descends as programmed to meet clearance and any crossing restrictions
AP-CAPTURES-ALT	AP captures altitude as programmed to meet clearance
AP-HOLDS-ALT	AP holds altitude as programmed

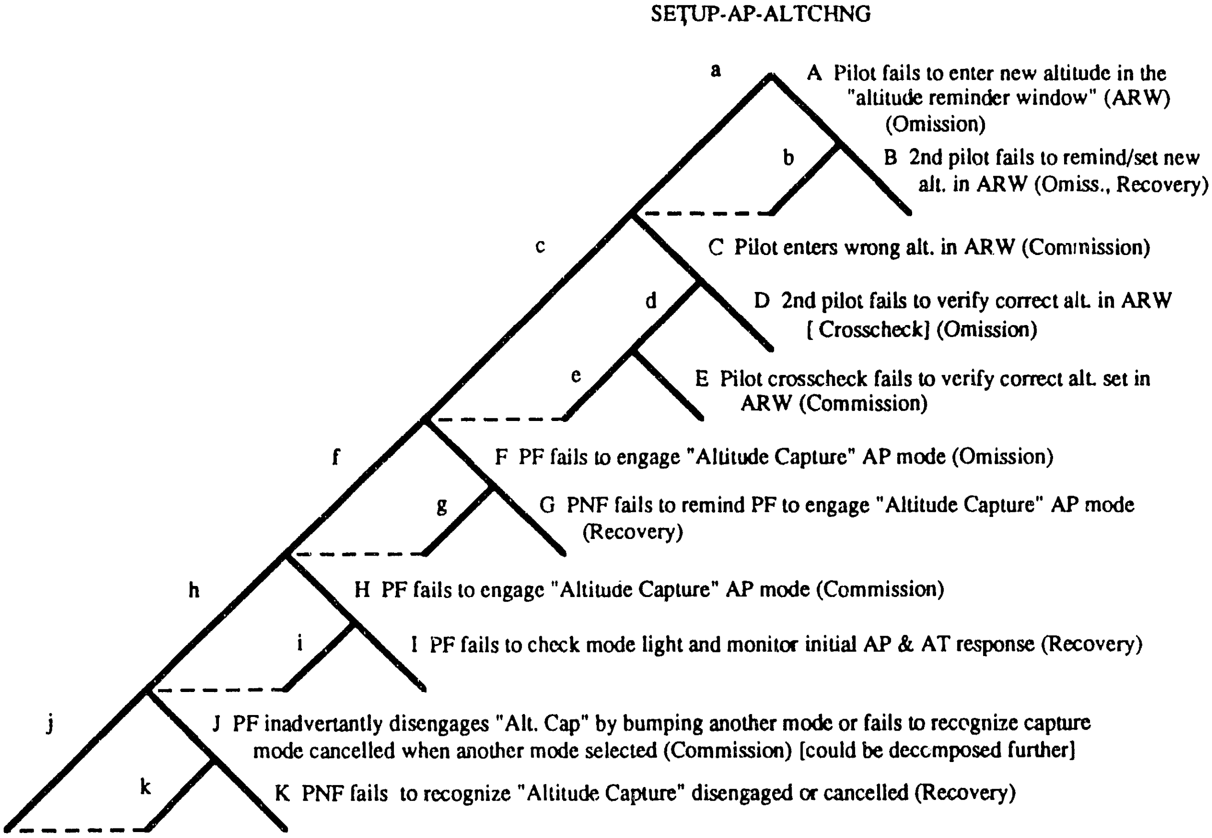

Figure 2. Setup-AP-Altchng HRA Event Tree.

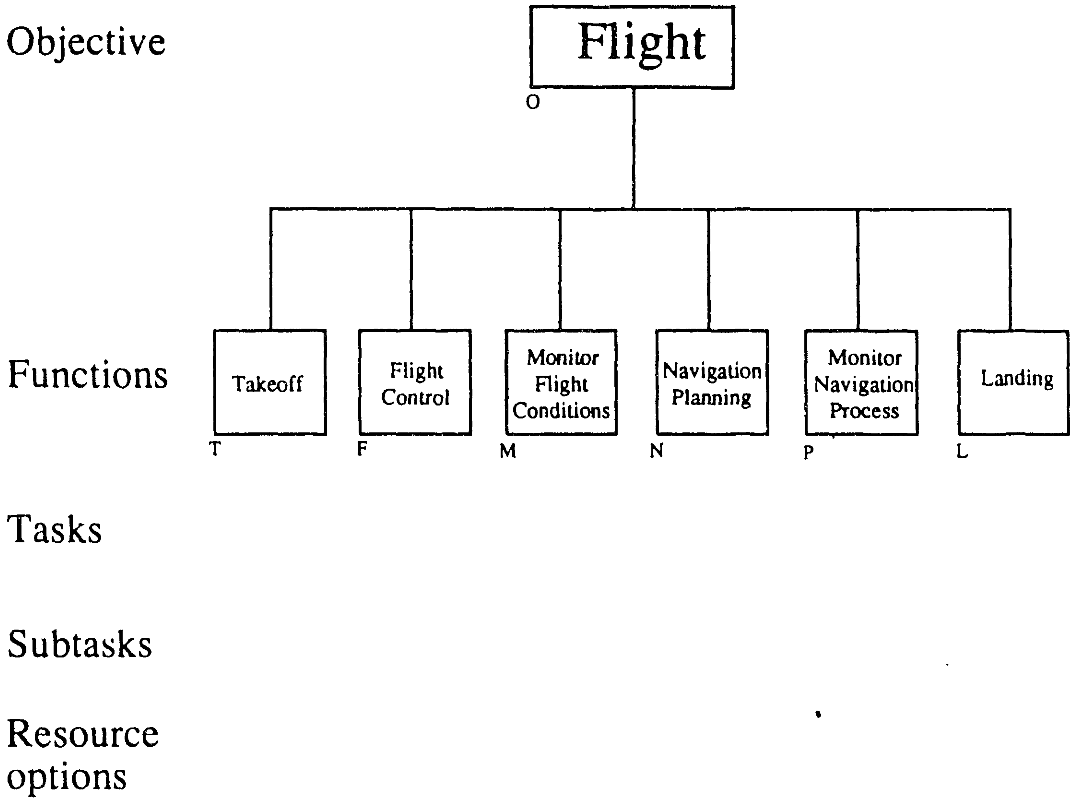

Figure 3. Overview of functional model of flight

B. Data.

The primary source of data used for this study of altitude deviation events was the Aviation Safety Reporting System (ASRS), NASA's third-party reporting system for incidents that occur in flight. The most common type of incident that is reported to the ASRS is altitude deviations, so the ASRS is a rich source of data regarding actual events.

C. Coding of ASRS reports.

Two hundred Aviation Safety Reporting System reports were reviewed. These reports were generated by a search of the ASRS database for reports that referenced Advanced Glass Cockpit Altitude Deviations. The reports were drawn from full-form records and describe altitude deviations that occurred between April 1991 and January 1992. These ASRS reports were subjected to an initial screening to identify those where the advanced technology (e.g. autopilot, flight management system, etc.) actually played a role in the incident. Then, the remaining reports were "mapped onto" the sequential and functional models to allow consistent interpretation. Mapping of the ASRS report onto the sequential model highlighted the location in the sequence of actions where the error occurred, whether available recovery paths were used, and what interventions could have been used to prevent such errors. Mapping of the ASRS reports onto the functional model highlighted the context in which the error occurred, and whether inappropriate attention to other critical functions contributed to the occurrence of the error.

D. Identification of error categories.

The coded reports were next plotted on both tree models to see whether any patterns emerged. The intent was to note whether the reports tended to cluster in certain areas of the functional and sequential models, or if the coded reports represented all areas of the models. These groupings were then examined to note where in the process of achieving and maintaining altitude the errors occurred. For purposes of this inspection and for visual presentation, the errors were mapped onto depictions of both models. The sample of ASRS reports analyzed for this study was small, and not necessarily representative of the entire spectrum of errors that can lead to altitude deviations. Probably even more important are the contextual insights gained by examining the different error categories in the situational contexts in which they occurred.

E. Callbacks.

The next step in our analysis approach was to perform callbacks on selected reports. Callbacks are the process by which ASRS personnel contact the individuals who submitted ASRS reports in order to obtain additional information about the circumstances of the specific incidents. An important feature of our approach was the use of the models to formulate specific questions targeted at the individual ASRS reports. This allowed us to focus the callback to elicit information so that we could interpret a specific report in context. The callback process was used in this study to further examine the effectiveness of the sequential and functional modeling tools. A second search was requested with the specific intent to collate reports which would be similar in content to the 31 previously coded reports, but available for callbacks (the previous reports were too far through ASRS processing to be available for callback). The 20 reports were reviewed by the INEL staff for applicability of the sequential and functional models. This review screened out five inappropriate reports; 15 reports were subsequently coded using the two models.

A set of callback questions was developed for each of the 15 reports. The questions were derived from examination of the sequential and functional models. The coding of each report was examined in conjunction with the models to see what questions the model structure provoked (i.e., what questions needed to be answered to allow the coding of the report to extend further into the models). A set of generic questions was also established to collect additional information of general interest.

III. RESULTS

A. Altitude deviation errors in advanced technology aircraft.

The application of model-based human error analysis has revealed many things regarding the characteristics of altitude deviation events in advanced technology aircraft. The mapping of ASRS reports of altitude deviations has provided a systematic method for classifying the errors that occur. These classifications can then be used to suggest remedies for preventing the errors or mitigating their consequences.

A matrix of ASRS reports and their sequential and functional codes is shown below in Table 3.

As Table 3 shows, sequential codes were distributed among 11 of the 13 event trees, with SETUP-AP-ALTCHNG (setting up the autopilot for altitude change) having, by far, the largest grouping. Groupings also occurred within the functional model, with the largest grouping under "Program Flight Management System (FMS)". These results fit with the hypothesis of this study that the crew interaction with the advanced cockpit is a source of errors which lead to altitude deviations. Within the grouping of errors, we observed that three specific types of errors were predominant.

- Errors that occurred because the flight crew did not understand the details of FMS functions. These types of errors could possibly be prevented by improved training regarding FMS functions, or the redesign of the systems so that the representation of status is more apparent to the crew.
- Errors that resulted from incorrect manipulation or monitoring of automated systems. This type of error could potentially be prevented by redesign of the displays and controls to provide better feedback to the flight crew.
- Errors that occur when the pilot understands the function of the autoflight systems, but errors have been introduced from an external source such as maintenance or design errors. These errors could potentially be prevented by a redesign of automated systems taking into account the pilots expectations of the system.

Table 3. Matrix of reports coded by sequential and functional models.

	Specify Altitude	Ground Communication	Achieve Desired Altitude	Obtain Clearances	Determine Location of Hazard	Form Navigation Plan	Program FMS	Monitor Altitude	Prepare Flight Plan	Specify Vertical Speed	Perform Final Approach	Achieve Desired Airspeed
Newalt-Clearance	x	x		x								
Pilot-Holds-Alt			x									
AP-Captures-Alt			xx		x		xx					
P-Captures-Alt			xxx		x		x					
Setup-AP-Altchange	x					x	xxxx xxxx		xx			
P-Altaware-1								xx				
P-Monitor-Altcap										x		
Baro-Set								xxxx				
P-Adjst-Altchng						x	xx				x	x
P-Altaware-2							x					
AP-Climb/Descnd							x					

Our study of altitude deviation errors has led us to a number of general observations about the factors that lead to these incidents. It appears that pilots have learned to rely on their automated systems, and have delegated control of not only flight functions, but also monitoring functions, to the automation. Thus, they are not watching for deviations to occur, but tend to assume that the autoflight systems will take care of altitude capture and maintenance. Some pilots seem to be predispositioned to assume that the automated systems will do what they (the pilots) expect them to do, when in some circumstances the automation "wants" to do something else. These factors imply that the role of the pilot has in some circumstances changed so that they are flying the flight management system rather than the aircraft itself. The final result is the relaxation of the pilot's instinct to "stay ahead" of the airplane and decreased vigilance regarding the maintenance of critical flight functions. In terms that are currently in vogue, advanced technology may in some cases actually reduce the flight crew's situation awareness.

B. Usefulness of the methodology.

We believe that the consistency and discipline that come with the development and application of task models have many benefits for the investigation of pilot errors in the aviation environment. For example, the development of task models provides a systematic approach to identify classes of errors, rather than relying on the natural instincts of the analyst. That is, models allow the analyst to successively investigate an issue to the necessary level of detail by expanding the models in the particular area of interest, until a sufficient understanding of an error type is obtained to suggest a remedy.

The analysis of the callback responses revealed that both the generic questions and the report-specific questions evoked useful information. The callback process was also effective in confirming the utility of the sequential and functional models. We believe that the use of the sequential and functional models to suggest report-specific questions for callbacks is an important feature of our approach. This technique proved valuable for discovering additional information that was not available from the original analysis of the ASRS report. The additional information was then used to characterize the specific event in more detail, and to enhance our understanding of altitude deviation errors. Such focused information could not have been gained from the use of generic callback questions. The report-specific questions allowed for maximum utilization of the callback process. The callback answers were also useful in that they identified areas where the sequential and functional models could be clarified, expanded, and made more aircraft-specific.

C. Application of Results to the Nuclear Industry.

The lessons learned from this study of pilot errors in advanced technology aircraft can be applied in the nuclear industry on a number of levels. On a high level, the general results obtained from this study can be used to sharpen our expectations of what we will observe when advanced technologies are introduced into the control rooms of nuclear power plants. We should not assume that the introduction of advanced technology will be an unmixed blessing, resulting only in reduced operator error and workload. Rather, we should probably expect that, similar to the flight environment, control room workload may decrease during periods of low activity, but that workload may actually increase during busy times such as mode changes or disturbances.

On a more detailed level, we may expect that some of the specific results obtained from the study of pilot errors may also carry over into the nuclear application. For example, it is quite possible that we may observe errors that result when reactor operators do not understand the details of the functioning of their advanced automated systems, or errors that occur when automated systems are activated or manipulated incorrectly. Because these errors still persist in aircraft after many years of experience, it would be beneficial for the nuclear industry to attempt to explicitly eliminate or compensate for these types of errors in the design of advanced systems.

Finally, we believe that the methodology used for this report could be put to use to identify and classify errors that occur when reactor operators utilize advanced technologies in the reactor control room. A systematic application of this methodology could be used to analyze operational experience to identify errors and to identify ways to eliminate these errors through design or procedures. It would be most beneficial to perform these studies before designs are finalized and implemented in operating reactors, for example, by performing experimental studies using prototype systems in the laboratory. It should also be possible to extend the modeling approach into the design process itself, to identify and eliminate errors before they are incorporated into the final system design.

Work supported by the National Aeronautics and Space Administration under DOE Idaho Field Office Contract DE-AC07-76ID01570.

IV. REFERENCES

1. N. B. SARTER and D. D. WOODS, "Pilot Interaction with Cockpit Automation I: Operational Experiences with the Flight Management System (FMS)," Draft, The Ohio State University, Cognitive Systems Engineering Laboratory (1991)

2. A. D. SWAIN and H. E. GUTTMAN, "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications," NUREG/CR-1278, U.S. Nuclear Regulatory Commission (1983).

3. W. R. NELSON and H. S. BLACKMAN, "Response Tree Evaluation: Experimental Assessment of an Expert System for Nuclear Reactor Operators," NUREG/CR-4272, U.S. Nuclear Regulatory Commission (1985).

END

DATE
FILMED
7/9/93