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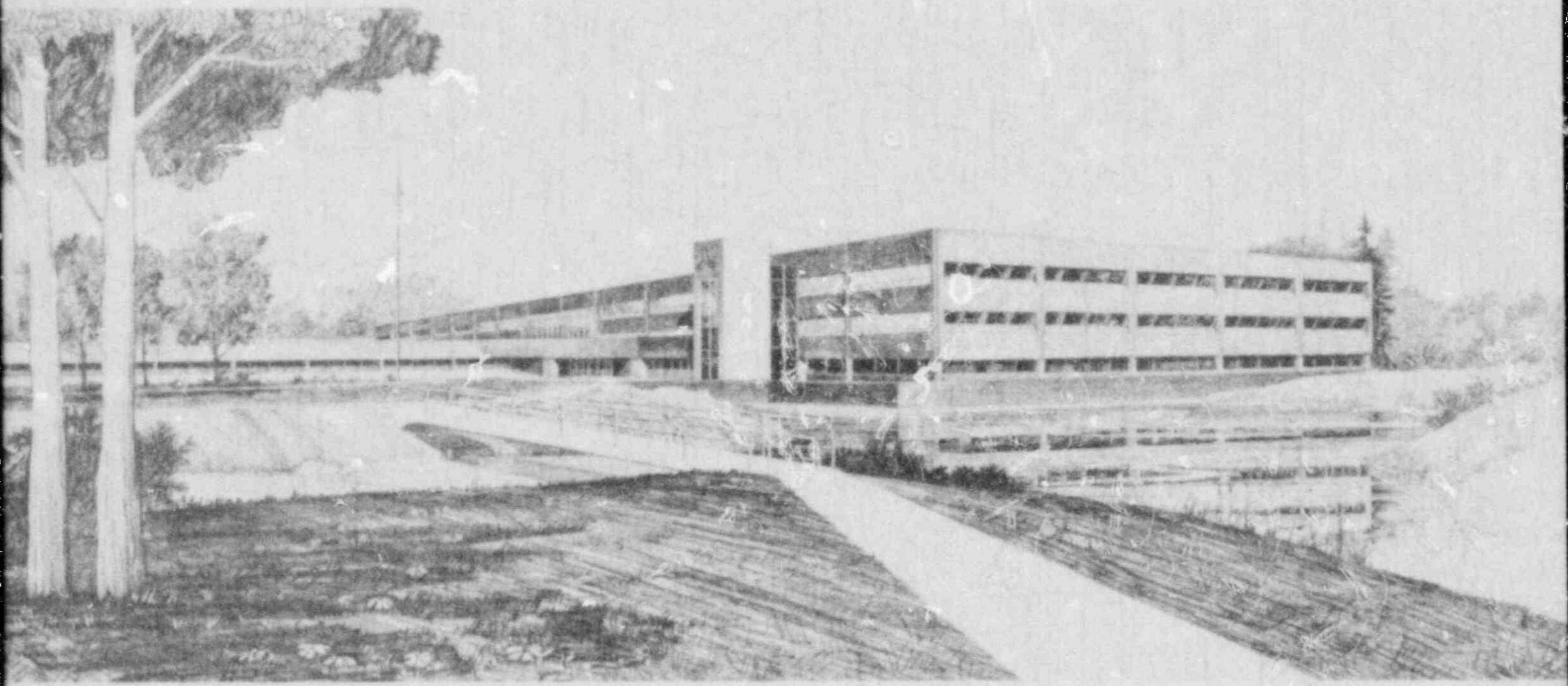

Idaho National Engineering Laboratory
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Alarms Within Advanced Display Systems: Alternatives and Performance Measures

Michael M. Danchak

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ABSTRACT

This study surveys five advanced alarm handling systems in industries having problems similar to nuclear process control. The survey identifies the uniqueness of each system as well as features common to all. One such common feature is the use of alphanumeric alarm message strings displayed on cathode ray tubes (CRT). The study presents alternatives for display of this information and dynamic techniques for the addition and deletion of alarms. A software package is described that incorporates the alternatives and allows low-fidelity experiments to be conducted in an environment that simulates nuclear process control. The package was used to test static aspects of alarm CRTs and led to the conclusion that quantitative data should come before qualitative data in alarm message strings. Methods for low-fidelity testing of display dynamics are also discussed.

FIN No. A6308—CRT—Display Design and Evaluation

SUMMARY

The intent of this study is to survey alarm systems within various industries for ideas on how to improve the alarm handling capabilities of nuclear process control applications. The survey concentrates on the display of alarm occurrences for the human operator and looks for uniqueness as well as commonality in display techniques. Any alarm system should concentrate on conditions rather than individual parameters. It should identify the problem, indicate the severity, and guide the operator toward corrective action. The five systems surveyed and their uniqueness are as follows:

- The Magnetic Fusion Test Facility at Lawrence Livermore National Laboratory has an integrated alarm system that addresses all three criteria and makes interesting use of touch panels for operator interaction.

- The HALO system at the Halden Project is stand alone and only attempts to address identification. However, groupings of alarm conditions in hierarchical fashion drastically reduces the number of alarms shown to the operator.

- The Diagnosis of Multiple Alarms (DMA) system at Savannah River uses logic trees, stored in the form of decision tables, to identify, diagnose, and correct problems associated with pipe leaks. The operator is advised only of the highest priority problem and can concentrate on its correction.

- The NASA Space Shuttle Caution and Warning System is an integrated system designed for highly trained operators. The actual alarm message string is closely keyed to diagnostic and corrective action procedures. The system first concentrates on achieving a safe state in a short period of time and then allows for longer range corrective action.

- The Aircraft Alerting System Standardization Study sponsored by the Federal Aviation Administration addresses the same problems that exist in nuclear process control.

The emphasis is not to dictate design, but establish minimum criteria. The resulting candidate systems are solidly based on human factors principles and provide excellent data on how to achieve the minimum requirements for visual and aural cues. The system uses both master indicators and detailed lists to address the first two criteria for alarm systems.

A point of commonality in all systems is the existence of an alphanumeric message string describing the alarm. However, little human factors work has been done on the content of that message string or the format for consolidated lists of existing alarms. Such work is necessary for future systems design as well as backfitting existing alarm CRTs. Alternatives for display arrangement are identified here, as are different dynamic methods of adding and deleting alarms. These alternatives are presented since there are no known validations of the currently used pushdown stack method.

A software package capable of implementing the various alternatives was designed for use in display evaluation. A situation "simulating" the conditions in process control was also devised for low fidelity experiments. This situation is one in which a "highly instrumented" automobile presents process control-like alarms to test subjects who are very familiar with and understand the workings of an automobile. The automotive technique and software alarm package was used to investigate the arrangement of information fields on a CRT. The results indicate that quantitative information, such as parameter values, should be listed first—followed by qualitative descriptions of the problem. Although display dynamic factor tests are beyond the scope of this study, a scenario method is presented whereby such tests can be conducted using the alarm software package and the automotive situation.

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ALARMS WITHIN ADVANCED DISPLAY SYSTEMS: ALTERNATIVES AND PERFORMANCE MEASURES

INTRODUCTION

The need for greater amounts of information to control industrial processes has closely paralleled the increase in complexity of these processes. Early systems designers quickly recognized the limitation of the human operator in trying to cope with all this information simultaneously. It was not possible for the operator to watch all the dials and meters all the time. A parameter that exceeded a specified value might easily be overlooked. Set points were then instituted to take advantage of a rudimentary "report by exception" technique that was redundant to the standard instrumentation. This quickly grew to an information system in its own right (i.e., an alarm system) and manifested itself in a myriad of annunciators and error-loggers now found in process control rooms.

Once again, however, the operator's ability to cope with large amounts of information has been overtaxed. Process control literature of the 1970's[1] repeatedly decried the fact that existing alarm systems were inadequate. This was particularly illustrated by the sequence of events at Three Mile Island.[2] Standard control room annunciators just cannot provide the information in the time and format required for intelligent response. The advent of computer-generated cathode ray tube (CRT) displays in control rooms provides a tremendous potential for rectifying this situation. They have been incorporated in most designs of the so-called "advanced control rooms."[3,4] Use of the CRT has many advantages in this application, but also many serious disadvantages. It is not sufficient to reproduce the annunciators or error-loggers in electronic form. Techniques for these older methods are not necessarily transferable. One needs to return to basics and answer some fundamental questions, the primary of which is the purpose of the alarm display.

The purpose of an alarm system should reflect the role of the operator in an alarm situation: it should alert, inform and guide toward actions.[5] "In alerting the operator of abnormalities or changes in status, the alarm function of a good operator interface will direct him to the proper corrective action."[6] The consensus is that the system must:

- Advise the operator of the occurrence of an abnormality
- Provide the means of evaluating the extent of the abnormality
- Provide a means of determining corrective action.

This allows the operator to quickly move through the various phases of the human decision-making model devised by Rasmussen[7] and modified by Pew[8] (Figure 1). The operator must be immediately aware of the abnormality (acquires data), its extent (understands the data), and be advised of corrective actions (evaluates and selects actions).

This does not imply that the three elements must be satisfied by this same display. Within the total alarm system, however, all these elements are necessary. With such requirements, it is immediately obvious that the need for a viable alarm system is not unique to nuclear process control. Any situation that requires human interaction should provide similar capabilities, whether the task is driving an automobile or flying the NASA Space Shuttle. Only the level of sophistication should change, based on operator response time and associated risks.

This study concentrates on alarming within advanced display systems, which implies process control-like applications. The nuclear power industry reasonably represents the state-of-the-art in this area, considering the "advance control centers" currently available from the Nuclear Steam Supply System (NSSS) vendors. However, commercial products require considerable lead time and detailed information is usually proprietary. Designers working in other industries, such as fusion and aerospace, are also faced with similar problems and their solutions are often overlooked by the power designers. Therefore, this study surveys the work being done in related areas and concentrates on the display solutions that have come about. It then looks at alternatives to those solutions as they might be applied to nuclear process control.

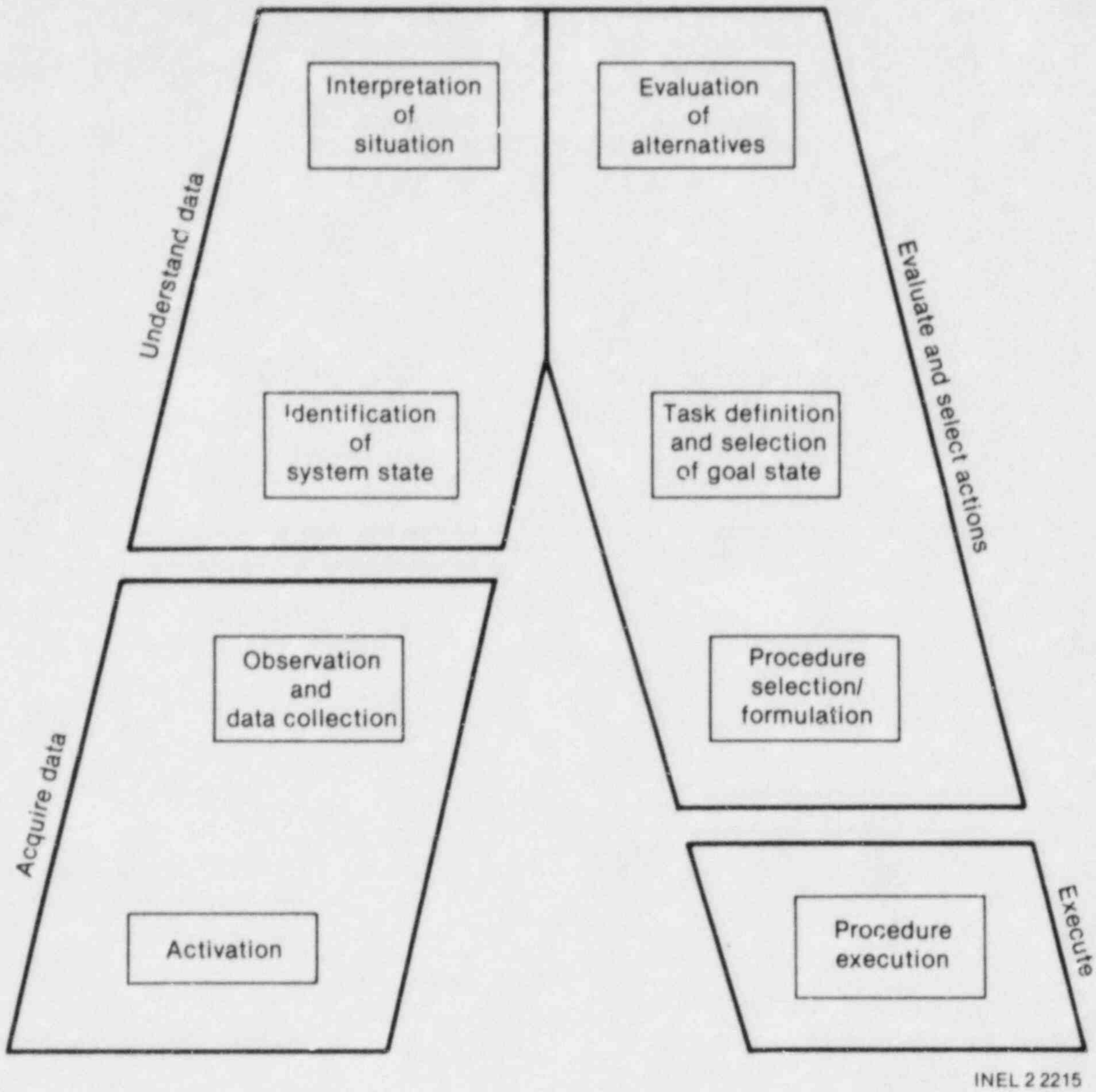

Figure 1. Rasmussen's model of human decisionmaking as modified by pew.[8]

Definition of Alarms and Alarm Systems

The term "alarm" has different meanings for different people, although there is commonality in the alerting aspects of the word. Historically, it relates to a call to arms or weapons. Webster defines it as a signal that warns or alerts. While the common usage definitions have elements of validity, the industry specific meanings are more important. Unfortunately, there is no single standard definition for an alarm in the nuclear industry. A reasonable one is "the action to alert attendants that a monitored signal has changed from a normal to an abnormal condition," found in Banks and Boone.[9] However, this definition emphasizes signals and also applies to the annunciator system that deals with less critical abnormalities.

The military has an accepted definition, but it reserves "alarm" for auditory systems. The comparable non-auditory term is "warning signal." The Military Standard (MILSTD) definition of warning signal is "a signal which alerts the operator to a dangerous condition requiring immediate action."[10] The military standard also defines caution and advisory signals for less severe conditions and levels of operator action. NASA has a comparable concept, in its Caution and Warning System, that "has the responsibility to alert the crew to out-of-limits conditions or improperly configured systems."[11]

The ideas behind caution and warning systems are perhaps closer to what is really intended for nuclear power plant operators than that of alarms. The response time of the human operator is such that true alarm conditions are best dealt with by hardware. A situation that threatens the health and safety of the public requires rapid response and is often triggered by a single parameter. Operator interaction is more appropriate when a condition, rather than a signal, becomes abnormal. The important difference being that a condition may be comprised of a number of measured parameters or signals, none of which are individually threatening. Changing commonly accepted terms, however, is not easy.

There is informal agreement that conditions should be annunciated rather than parameters, but the industry still basically concentrates on signals in its existing caution and warning systems. New systems being developed change the emphasis from "individual alarms" to "integrated alarm systems."[12] While the intent of this study is to concentrate on the display aspects of those new systems, one can not ignore the hardware problems involved in making that change.

Evolution of Advanced Systems

As discussed in Edwards and Lees,[13] most alarm systems treat three types of problems: absolute values, deviations, and instrument alarms. When a measured signal value becomes too small or too large for the intended process, the system will annunciate that fact to the operator. A deviation of some specified amount from a set point, often determined by the operator, will also trigger an alarm; as will a zero or full scale reading of a given instrument. Individual signals are directly tied to status lights or annunciator windows, as shown in Figure 2, to perform the "one measurement—one indicator" function described by Goodstein.[14] For analysis purposes, this configuration was labeled the "hardwired" approach and is prevalent in exiting nuclear power plants. The emphasis here is on individual signals.

Figure 3 represents an improvement over the hardwired approach in that multiple signals are logically combined to produce a single output. The logical combination may be a voting scheme (i.e., two out of three) or other Boolean functions. The net effect is to reduce the number of indicators that require operator attention. Use of this technique may be found in recently designed annunciator systems and hardwired safety systems. The latter, of course, are more concerned with control rather than with display.

A third configuration is one that replaces the hardwired logic with software, Figure 4. A computerized data acquisition system is used to centrally process input signals. The standard voting logic is available, along with filtering and signal processing algorithms, and the output is often sent to CRT displays. This configuration is typical of that found in the "Advanced Control Centers" available from NSSS vendors and represents a substantial change in the detection and processing of abnormal signals. Efforts are now being made to create an integrated information display, such as the Safety Parameter Display System (SPDS).

The last configuration, Figure 5, shows the state-of-the-art in alarm systems. An additional box is added to the data acquisition system to

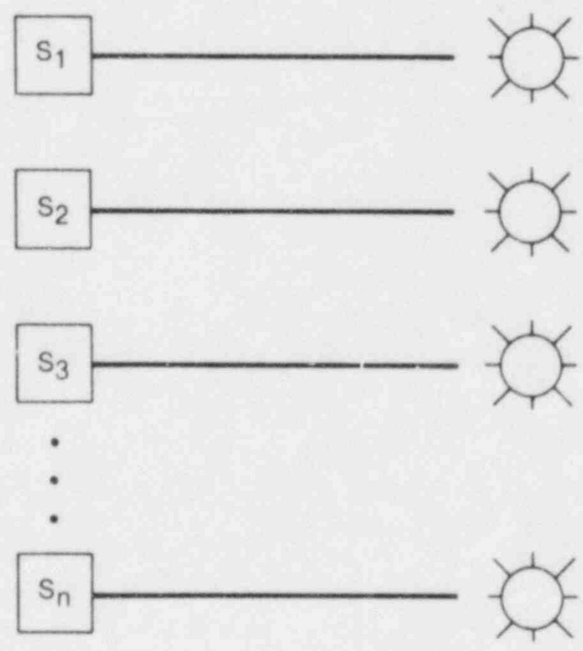

Figure 2. Hardwired configuration for alarm systems.

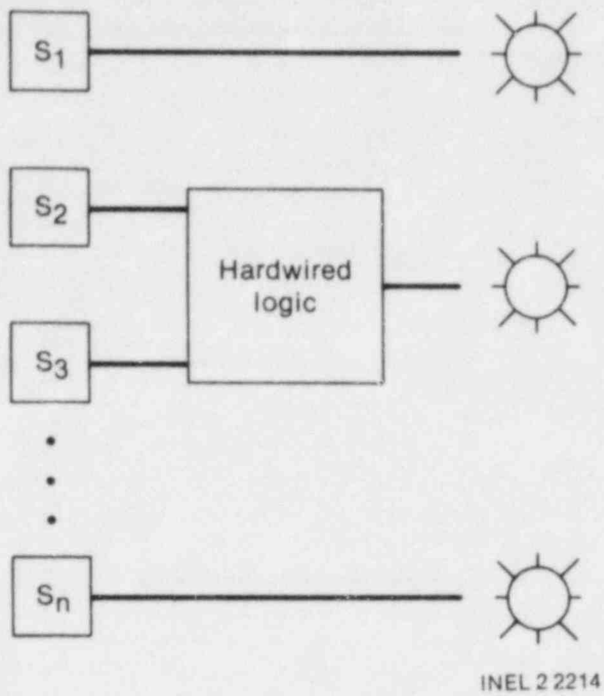

Figure 3. Hardwired with logic configuration for alarm systems.

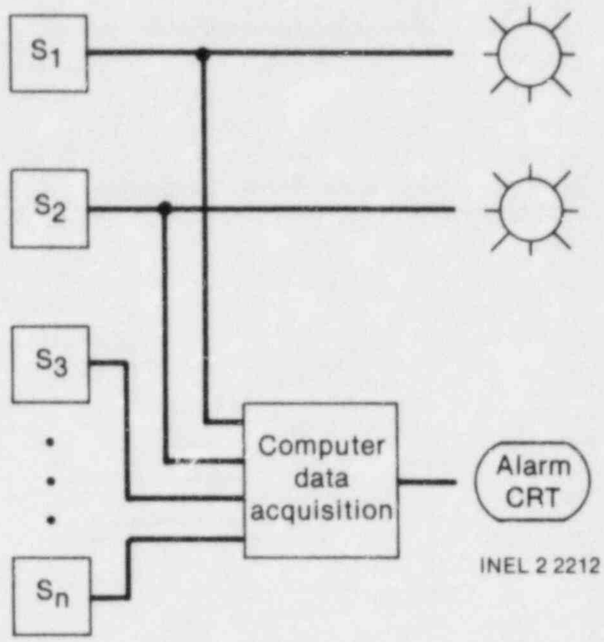

Figure 4. Computerized data acquisition configuration for alarm systems.

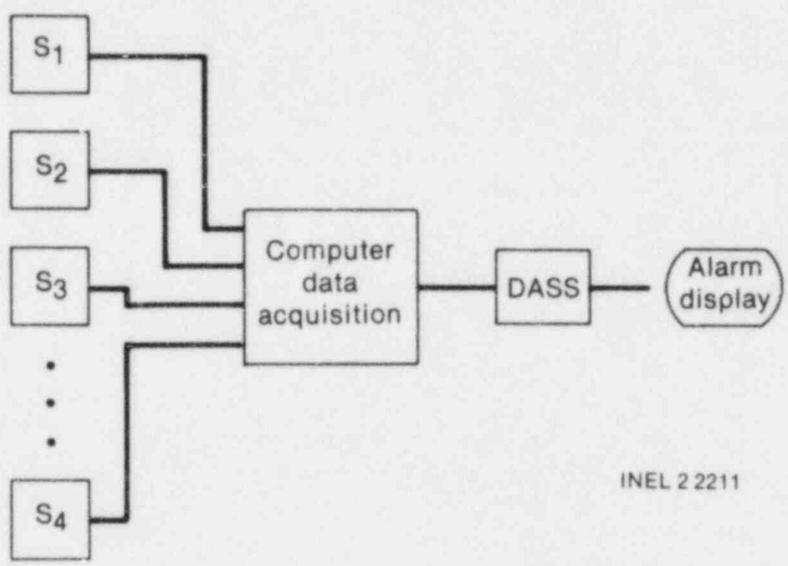

Figure 5. Disturbance analysis and surveillance configuration for alarm systems.

allow real-time execution of fault trees, cause consequence diagrams, and/or mathematical models. This technique is currently receiving a great amount of attention, particularly by the Electric Power Research Institute (EPRI) and its Disturbance Analysis and Surveillance System (DASS) projects. The construction of the system itself is a very difficult task, but results to date are very encouraging. Once the knowledge of how to implement systems becomes available, more attention should be given to the display of the data for operator use.

The four configurations just discussed will be used in describing the state-of-the-art survey of alarm systems in related industries. It is important to understand the capabilities of the system before one can discuss the display aspects. In most advanced systems, CRTs play a prime role in the operator/process interface. The existence of appropriate hardware, such as computers and CRTs, and software models and algorithms provide the potential for an integrated alarm system. The crucial question is whether the hardware is being used effectively.

STATE-OF-THE-ART SURVEY

As stated previously, one objective of this report is to survey how related industries incorporate alarms within advanced display systems. Candidates for the survey are limited because nuclear power industrial systems typically reflect or exceed the norm in process control. However, much innovative alarm work is being done in the areas of fusion and noncommercial reactors. The aerospace industry also has similar problems and has an excellent reputation for paying attention to human factors. The intent here is to present the solutions devised by these designers and learn from their efforts. No single system can be judged the ultimate. However, parts of each solution can be merged to form a viable system that greatly improves on those currently available.

Five representative systems from two areas will be discussed. Each system will be described in general and then the display techniques analyzed. The analysis will be presented as answers to questions posed in Table 1. These questions relate to the alarm system functions mentioned earlier and try to determine the purpose of the surveyed system and its operations. The display questions look at format, arrangement, and dynamics. Format is the general makeup of the display. Is the display a string of alphanumeric text, a graphic representation such as circular profile,[15] or a combination of both? Arrangement is placed on the display. Dynamics are related to the number of alarms per display and how these alarms are added to or deleted from the display as the process being controlled operates.

Table 1. Questions asked of surveyed systems

Definition and purpose of alarming

How is information to be displayed determined

Extent of computer aiding

Display format

- Alphanumeric
- Graphic
- Hybrid

Display arrangement

Display dynamics

- Number of alarms/page
- Addition of alarms
- Deletion of alarms

Nuclear-Related Systems

Control of nuclear processes typically brings to mind commercial plants and their associated control rooms designed and built by NSSS vendors and architect/engineers. However, there are a number of nuclear-related systems, often involving a reactor, that have sophisticated display and alarm techniques. While the processes may be somewhat research oriented, the day-to-day control presents problems very similar to those of commercial systems. A distinct advantage of these systems is the shorter lead time required to incorporate developing technology and ideas. This section will present three such systems and analyze their solutions to the alarm handling problem. The first is a research fusion project, the second a European research reactor, and the last a Department of Energy (DOE) system at Savannah River. One must keep in mind that the alarm systems discussed are only part of a much larger control activity.

The MFTF Exception Handling System. The Magnetic Fusion Test Facility (MFTF) is located at the Lawrence Livermore National Laboratory and is funded by the Department of Energy as part of its fusion research program. The control system is responsible for preparatory opertions for experiment readiness, maintenance of such readiness, synchronization of plasma shots (experimental operations), and returning to the shutdown state.[16] The MFTF Exception Handling System operates as part of the Supervisory, Control and Diagnostic System (SCDS) which comprises seven operator control consoles arranged in hierarchical fashion, Figure 6. The supervisor control console has six screens and two touch panels while each subsystem console has three status screens and two touch panels.[17] The Exception Handling System is in addition to a hardwired protection system that is primarily responsible for the health and safety of the public.

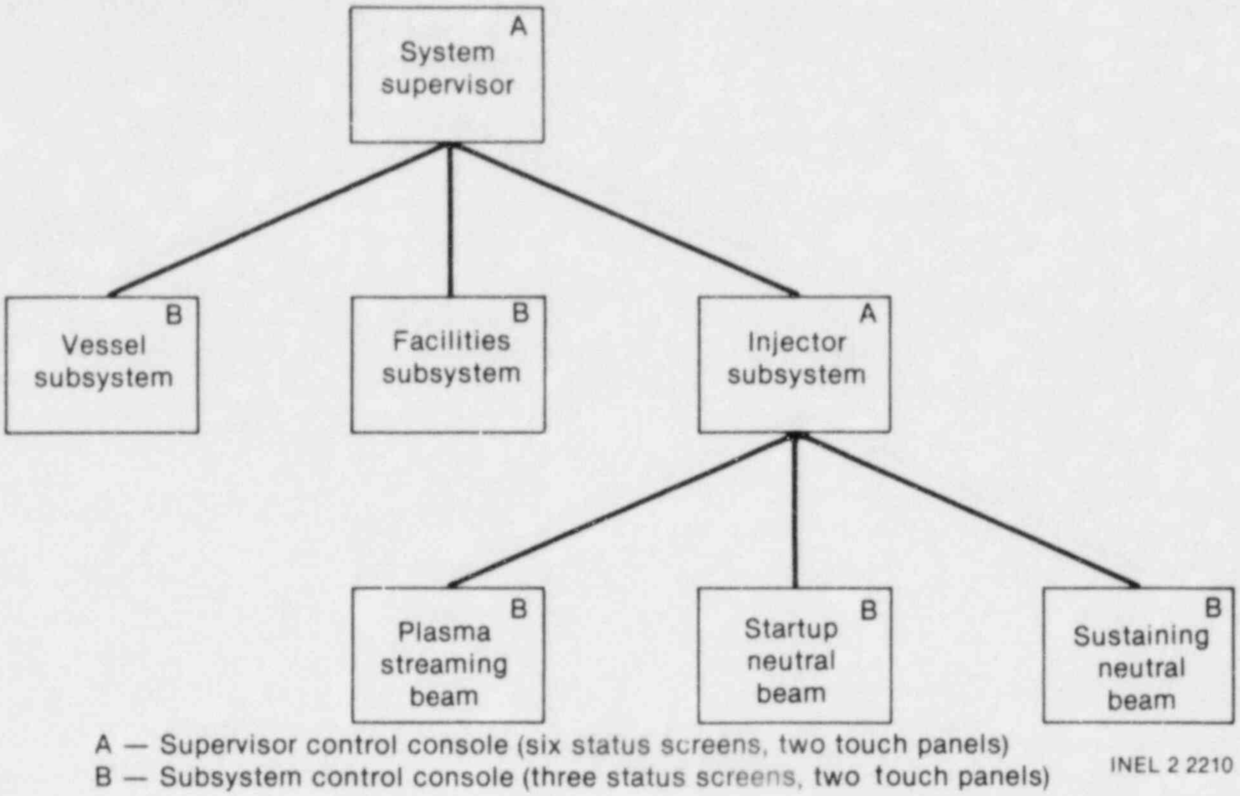

Figure 6. Supervisory control and diagnostic system console configuration for MFTF.

An exception is defined as a deviation from normal operating conditions and is reflected by a change in state of a monitored value (high critical, high alarm, low alarm, and low critical), a change in a status signal, or degradation in the performance of certain operations. A return to normal is treated as an exception itself. The system purposes are:

- Detect exceptions and report them to the operator
- Provide an audit trail or event analysis and safety review
- Back up the hardwired protection system
- Help in detecting abnormal trends before hardwired action is taken
- Aid in identifying malfunctioning sensors.

The SCDS itself monitors approximately 1,000 points, any of which has the capability of becoming an exception. A computer data acquisition system collects and disseminates information and performs some smoothing functions on the points.

The display format for the alarms is alphanumeric and may appear as a one-line message string on a central display called the "Exception Attention Message" or as an expanded message string on a "Consolidated Exception List." The central display is used for normal control and contains mimic and graphic representations. The operator may request the exception list by interaction with a light button on the touch panel.

The exception attention single-line message shows the number of exceptions waiting to be listed and a brief description of the highest priority exception yet to be listed. When the operator requests the exception list, new exceptions are added to that consolidated list.

The exception list has seven fields arranged in a left to right horizontal fashion. The field contents are illustrated in Figure 7 and are defined as follows:

LINE #	RESPONSE FIELD	EXCEPTION FIELD	PRIMARY SUBSYSTEM	DATE	TIME	EXCEPTION DESCRIPTION
1	ACKNOW	9125	CYRO	12/12/81	10:06:04	Lite Level in Storage Dewar Down 75%
2	HOLDING	7238	VAC	12/12/81	10:05:15	Vessel Pressure Rising
3	OK ACTION	5121	CRYO	12/12/81	10:00:00	Cryo Panel 4 Temperature Rising
4	ACKNOW	8344	MAG	12/12/81	09:59:10	Magnet Warning Sensor 4
5		2771	PSF	12/12/81	09:58:07	Plasma Streaming Gun Unit 177 Failing
6	ACKNOW	3433	GET	12/12/81	09:00:00	New Getter Wire Inserted:88
7	ACKNOW	7127	CRYO	12/12/81	09:21:03	Cryo Panel Dewar Pressure Rising
8	ACKNOW	1290	VAC	12/12/81	08:20:05	Vessel Pressure Normalized

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Figure 7. Example of MFTF exception handling display.[16]

- Line number—an increasing sequential number assigned to each line of the CRT
- Operator response—a message that dictates the type of operator response for the exception
- Exception number—a unique number preassigned to each possible exception
- Primary subsystem—a code for the primary subsystem involved
- Time of occurrence—date and time the exception occurred
- Description—maximum of 40 characters describing the exception. A light blue check at the left edge of the message indicates the exception is a return to normal. The operator may also request an expanded exception description display to get more information on the problem.

The Exception List is a pushdown stack with a capacity of 22 new exceptions per page located on the top half of the CRT. A push down stack lists the most recent additions at the top, pushing older ones further down the display, much like a plate dispenser in a cafeteria. If more than 22 new exceptions are waiting to be displayed, the oldest 22 are shown first and the count on the Exception Attention Message decremented by that amount. An additional touch of the "List Exception" button will bring in a maximum of 22 more. The bottom half of the CRT allows the operator to scroll the entire list of exceptions up to a maximum of 75.

Messages are removed from the list either by explicit operator action or inverse chronological order when the buffer size of 75 is exceeded, regardless of the action taken. To correct an exception, the operator would touch the "Process Exception" button and interact with the system through the CRT. Once the fault is corrected the operator may remove the corrected exception from the report.

The MFTF Exception Handling System attempts to satisfy all three desirable alarm system functions with an integrated approach. The messages on the central display and exception list identify the alarm for the operator and use a color code to indicate severity. Light blue is used for return to normal, yellow for an alarm condition, and red for critical situations. An audible alarm is used only when the exception condition involves a high degree of danger. The "Process Exception" display also provides guidance to the operator in determining the appropriate action to be taken. At the time of this survey, neither the system nor MFTF was operational and therefore performance evaluation has yet to be done.

HALO. HALO is an acronym for Handling of Alarms with Logics and is a research project in progress at the Halden Reactor Project in Halden, Norway. The basic assumptions[18] of the system are as follows:

- The function of HALO shall be to alert the operator and to direct his attention toward off-normal conditions
- HALO will not analyze dynamic disturbances, predict consequences, or propose counter measures
- The system will present only status information, not analog data

- The system will not provide a recording of the conventional sequence of events with related time resolution
- HALO is self-contained
- The system will use color displays
- The time delay shall not be more than one second.

Although HALO represents an integrated alarm system, there has been no attempt to integrate the alarm functions into the operational displays as found in the MFTF approach. Hence, it provides an interesting contrast in philosophy.

The purpose of HALO is to alert the personnel in the control room and direct their attention, thereby satisfying the activation phase of the human decision-making model. It also gives some support in the observation and system identification phases, but does not try to take part in the actual decision-making of the operators. It attempts to provide a clear overview of the system, similar to the SPDS, but also incorporates nonsafety-related signals.

The configuration of HALO is basically a computerized data acquisition system with logic included for alarm suppression. This feature is important in any viable alarm system to reduce the number of nuisance alarms when the process is in a mode in which the measured parameter does not apply. For instance, one would expect all reactor pumps to be off in the shutdown mode, whereas they should be on during power operations. The ability to suppress an alarm triggered by the pumps being off during shutdown is extremely desirable, but not always present in existing systems.

HALO uses a hierarchical approach to display information and changes display format with hierarchical level. The highest level display is called an Overview and uses a schematic diagram or graphic format, to represent all the major subsystems in the reactor. The next level display, called the Alarm Group Detail, also uses a graphic format in the form of a mimic diagram. This display shows the details of one of the subsystems represented in the Overview. The lowest level display is a list of strictly alphanumeric text strings that show time of occurrence, an identification code and an alarm message in plain language. The alarm text display can be reconfigured to show all current alarms or alarms relating to a specific group or alarm class.

Alarms are indicated by color and blinking on the two graphical displays, much like the annunciator windows. However, the use of subsystem groups greatly reduces the total number that are presented at a given time. The alphanumeric text display lists the alarms in chronological order, using the pushdown stack principle described previously. HALO has no explicit reset function. When a parameter returns to normal, the alarm is immediately removed from the display without operator interaction.

HALO advises the operator of the occurrence of an alarm but, by design, makes no attempt to indicate severity or what to do next for corrective action. The logic involved concentrates on alarm suppression and emphasizes status rather than values. This system is also in development and is evolving through interaction with participants in the Halden Project.

Savannah River System. The third nuclear-related system is the Diagnosis of Multiple Alarms (DMA) system being installed in the three reactors at the Savannah River plant at Aiken, South Carolina. This facility is operated for the Department of Energy by the Du Pont Company. The current version of DMA concentrates on the detection of pipe leaks in the primary and secondary coolant system, but can be extended to the entire reactor.[19] The objectives of the system are to:

- Detect and locate leaks
- Analyze the need for manual emergency cooling water addition
- Direct operators to the correct written procedures
- Display leak rates
- Display control room radiation conditions.

Currently, the system monitors 150 leak-related annunciator signals and 40 process parameters.

A unique feature of DMA is in the processing of input data rather than display of messages. It represents a limited form of a Disturbance Analysis and Surveillance System in that the process control computers perform filtering as well as logical analysis. Whenever an alarm changes state (i.e., is triggered or corrected), the computer checks the input signals for persistence and validity to filter out spurious or fluctuating signals. It records the new state of the alarm and executes the DMA program. The DMA program uses decision tables to detect patterns of alarms that may indicate a coolant leak. Alarm patterns, in the form of logic trees, are stored in the decision tables. If appropriate conditions exist, a "primitive decision" is generated, which has an associated alarm message. This "primitive decision" is passed on to higher decision levels, each having a unique message. The end result is the display having the highest assigned priority. The DMA program executes in its entirety every time any of the alarm inputs change state. Currently, the designers can "tune" the sensitivity of the analysis, based on experience and judgment, without programming changes. Ultimately, the operator may be given the capability to make the system "more" or "less" sensitive.

The display format, shown in Figure 8, is alphanumeric but does not use the standard text string arrangement. Only one message at a time is shown on the CRT. The message specifies the type and location of the highest priority problem and refers the operator to procedures that will correct that condition. The lower left area of the screen displays the leak rate to indicate severity. The lower right area displays conditions in the reactor control room to assure the operator that his personal safety is not being jeopardized and allows him to concentrate on solving the problem. If his personal safety is threatened by high radiation levels, the display would flash "EVACUATE."

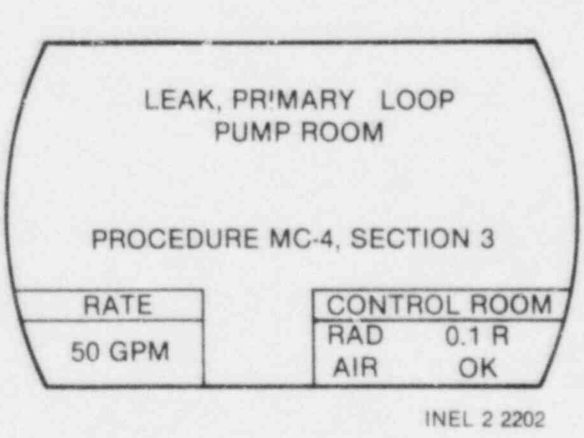


Figure 8. DMA alarm analysis display.[19]

The DMA system satisfies all the functions of an alarm system: it identifies the problem, indicates its severity, and provides guidance for corrective actions. The designers have taken an intelligent approach to a complex problem by subdividing it into more manageable pieces. Success in detecting leaks will prove the concept and allow it to be expanded to other areas via the inherent flexibility of decision tables. Furthermore, much emphasis has been placed on the software engineering aspects of the DMA program to allow for validation and verification.

Aerospace-Related Systems

Human factors and aerospace systems have been closely aligned since World War II. As pointed out by Chapanis: "Machines do not fight alone."[20] The need to account for the human element in military systems, particularly aircraft, was evident during these war years and gave birth to the interdisciplinary field of human factors. Since that time, much emphasis has been put on the "systems" approach, which ranks the human on the same or higher level as the machine.[21] The success of the space program and commercial aviation must be largely attributed to this concern for the human. Surprisingly, however, the results of a survey of aircraft caution and warning systems done by Cooper[22] in 1977 were that:

- There are too many warnings
- Reliability of warnings needs to be improved to reduce false alarms
- Warnings should be prioritized
- More automatic systems are needed to reduce crew workload.

One might conclude from this that the aerospace industry is no better off than the nuclear industry in the area of alarm handling. Fortunately, a great deal of effort has been expended since that report to correct the deficiencies of aerospace caution and warning systems. This survey chose to report two such systems: the NASA Space Shuttle and the proposed Standards for Aircraft Alerting Systems. The space shuttle system is obviously in place and functioning whereas the aircraft system is just out of the study phase. Both present interesting ideas that are applicable to the nuclear industry.

NASA Space Shuttle. The caution and warning system aboard the NASA Space Shuttle was designed by the Johnson Space Center and completed in 1978. The system is based on five alarm classes and uses a number of audio and visual cues, shown in Table 2.[22] There are four master alarm lights distributed throughout the cockpit that light for all Class 1 and 2 alarms. The caution and warning annunciator light matrix, Figure 9, is similar to the annunciator windows found in nuclear power plants. However, the shuttle system annunciates groups rather than individual signals. The system management alert light serves as a master alert for the Class 3 alarms. Three CRTs are available to show operational data, but a single pushbutton allows display of the fault messages.[23]

The caution and warning system has the responsibility to alert the crew to out-of-limit conditions or improperly configured systems. The system measures 129 parameters in 13 subsystems and depends on hardwired annunciators for primary alerting and a computerized data acquisition system for backup. All displays in the shuttle system are alphanumeric text strings rather than graphic displays. Operational displays have a single "fault message" line at the bottom showing the most recent fault. A combined list is available by pressing the "fault message" button. Figure 10 shows the string format for both the single line and combined list. The fault display has a capacity of 15 messages that are added to in a pushdown stack manner. Messages are removed by operator interaction using the MSG REST function button.

The shuttle caution and warning system is very straightforward and designed for highly trained operators. The indicator lights and fault line messages quickly tell the crew what is wrong. The CRT ID tells the crew member which CRT page has operational data concerning the problem, i.e., the severity. The fault text is closely keyed to hardcopy procedures indicating the necessary corrective action. The procedures provide a two-step corrective action response. The first step references a short checklist that puts the system in a safe state and is used in the first five minutes of the fault occurrence. This essentially buys time to refer to more detailed malfunction procedures, which deal with longer corrective action.

The beauty of this system is hidden by its simplicity. For example, assume a crew member receives the following indicators:

- caution and warning tone
- master alarm light
- "Freon loop-" caution and warning annunciator light (Figure 9)
- "S88 EVAP OUT T 1 -" (fault line message flashing).

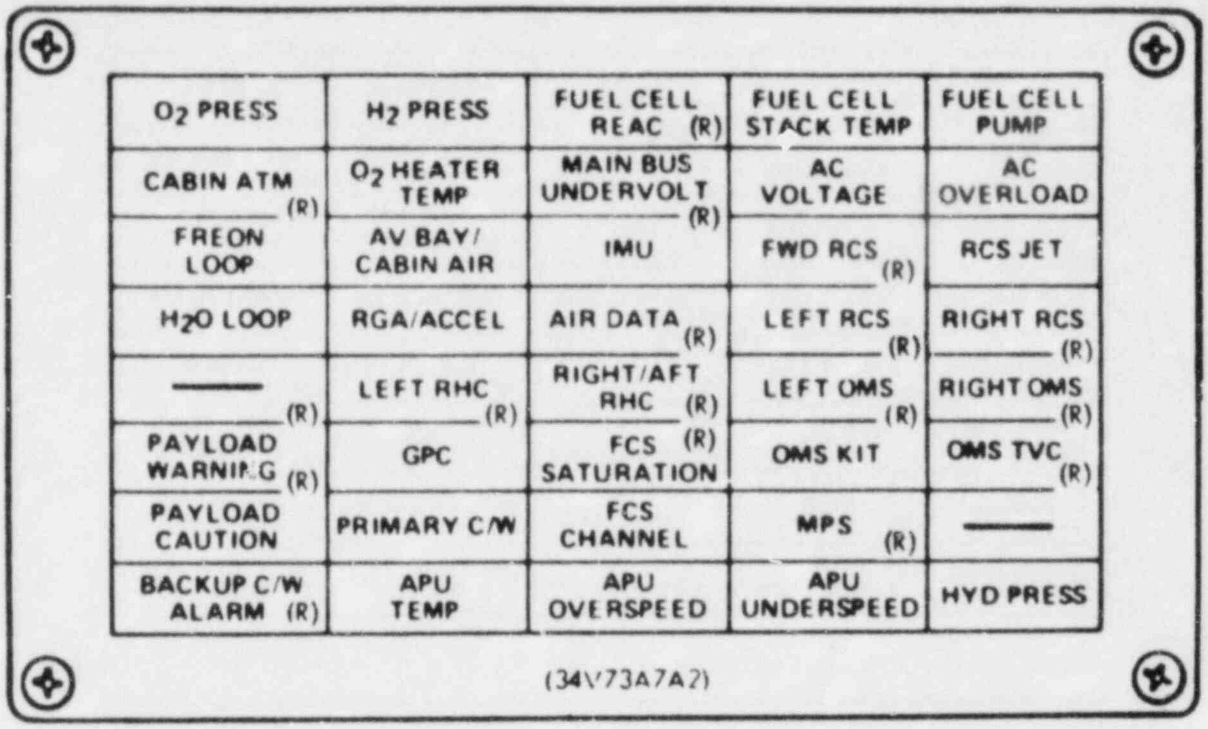
The crew member would depress the master alarm pushbutton indicator to extinguish the master alarm light and caution and warning tone. Pressing the ACK key on the keyboard would stop the flashing of the fault line message. The crew member would then request display "S88" to view the data shown in Figure 11 and refer to the pocket checklist keyed to this message, for immediate action. Longer-range corrective action is illustrated by Figure 12, a portion of the system malfunction procedures.

The integration of the alarm message string with related data is impressive. The message tells the crew member where to go for more information (CRT ID) and the corrective actions are listed by the fault text message for easy reference. The system requires prior definition of all possible alarm conditions along with their respective corrective actions, a seemingly impossible task for a nuclear reactor application. However, the use of references to operational displays is important for any system integrating alarms with operations. The keying of procedures to alarm text is also interesting, whether or not the alarms are integrated with operations.

Aircraft Alerting. An excellent summary of aircraft alerting systems at the start of this decade is given by Thompson:[24] "The State-of-the-Art Caution and Warning Systems (CAWS) is one of nonstandardization, inadequate evaluation of new displays, excessive numbers of non-prioritized alerting stimuli, and lack of intelligent automaticity in CAWS design." This condition is being addressed by a study sponsored by the Federal Aviation Administration (FAA) and headed by the Boeing Commercial Airplane Company, with participation by the Lockheed California Company and Douglas Aircraft Company. The objective of the study is to provide criteria for numerous acceptable system concepts that will promote functional standardization. Entitled "Aircraft Alerting Systems Standardization Study," the project has three phases: the first is to evaluate the elements of alerting systems and provide

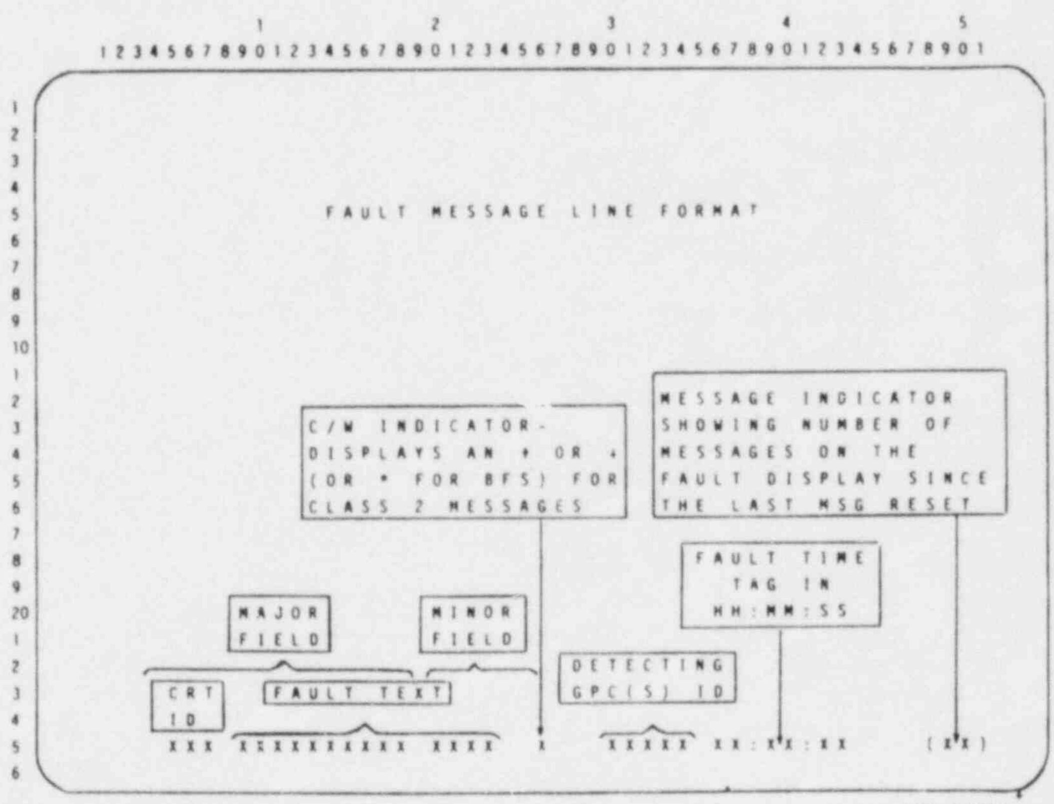
Table 2. NASA shuttle crew alarm annunciation summary

	Class 0	Class 1 (emergency)		Class 2 (caution and warning)		Class 3	Class 4 GPC	Class 5
	Limit Sensing	Fire/Smoke	Rapid ΔP	Primary R13 Panel (hardware)	Backup (software)	Alert	Detected Error (not used)	Operator Error
Audio alarms								
Caution and warning tone	—	—	—	√	√	—	—	—
Klaxon	—	—	√	—	—	—	—	—
Siren	—	√	—	—	—	—	—	—
System management tone	—	—	—	—	—	√	—	—
Visual cues								
Master alarm light	—	√	√	√	√	—	—	—
Caution and warning annunciator light	—	—	—	√	√	—	—	—
Backup caution and warning light	—	—	—	—	√	—	—	—
System management alert light	—	—	—	—	—	√	—	—
Smoke detector light	—	√	—	—	—	—	—	—
Fault message CRT	—	—	—	—	√	√	—	√
Status symbol on CRT	√	—	—	—	—	—	—	—



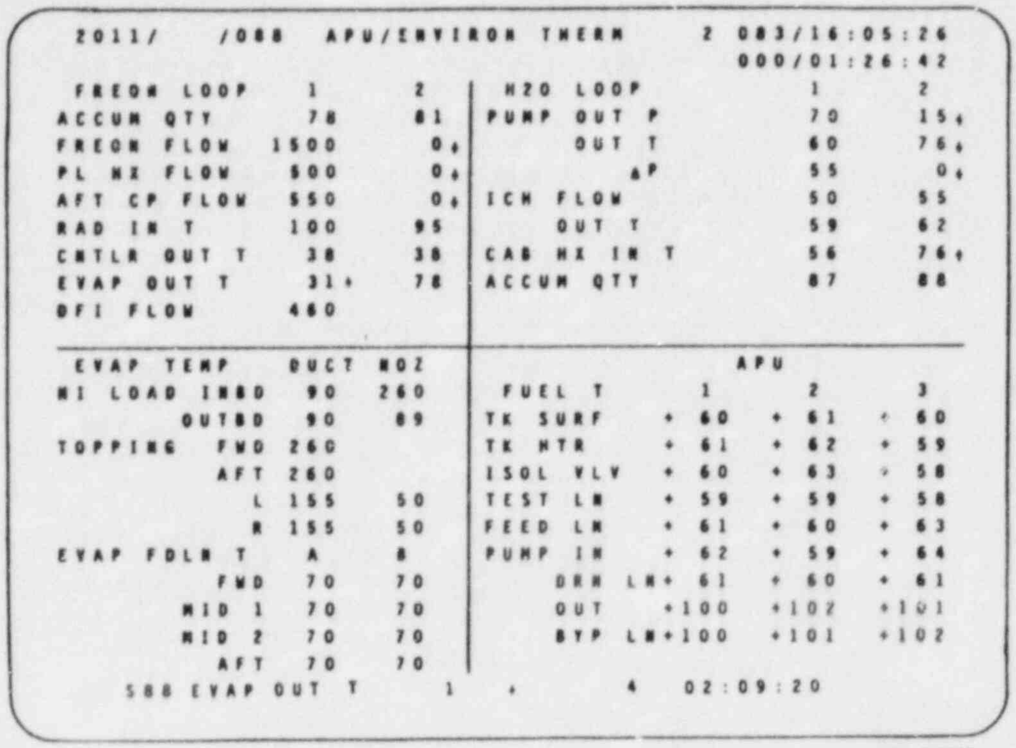
INEL 2 2204

Figure 9. NASA caution and warning annunciator panel.[11]



INEL 2 2206

Figure 10. NASA CRT fault line message format.[11]



INEL 2 2205

Figure 11. NASA APU/Environ therm operation display.[11]

candidate systems for evaluation, the second provides a detailed test plan for evaluating the candidate systems, and the third uses qualified pilots operating simulators to evaluate those candidate systems. The final report for Phase I is available[25] and is an excellent compendium on alerting. It also illustrates the results of good human factors work.

The objectives of the alerting system are:

- To increase the efficiency of the alerting process
- Minimize the time for the flight crew to detect, assess and response to alerts
- Reduce the demand on crew information processing and memorization capabilities
- Be flexible enough to permit growth
- Provide a system that can become a standard.

The results of the FAA final report are summarized in Tables 3 through 5. Table 3 identifies four conditions that should be alerted and their associated characteristics. Two candidate systems were developed by the study, based on these characteristics and differing only in the voice information display component. Both systems have master visual alerts for warnings and cautions. A master aural tone is included for these conditions as well as for advisories. A central visual information display presents alert messages for warnings, cautions, and advisories.

The function of the master cues is to alert the crew to the occurrence of high-priority events and to guide crew action by indicating the level of the alert (warning, caution, or advisory). Table 4 lists the variables associated with each type of cue and the recommended values. The master visual alert consists of a single split-legend annunciator window located within a 15-degree cone of the pilot's visual centerline. The window is labeled "warning" and "caution," coded in red and yellow respectively, and does not flash. Three master tones will be used. The warning tone will be intermittent and contain both high- and low-frequency components. The caution tone will be constant and midrange in frequency (2000 to 4000 Hz) while the advisory will be a single-stroke, low-frequency tone. A unique feature is the inclusion

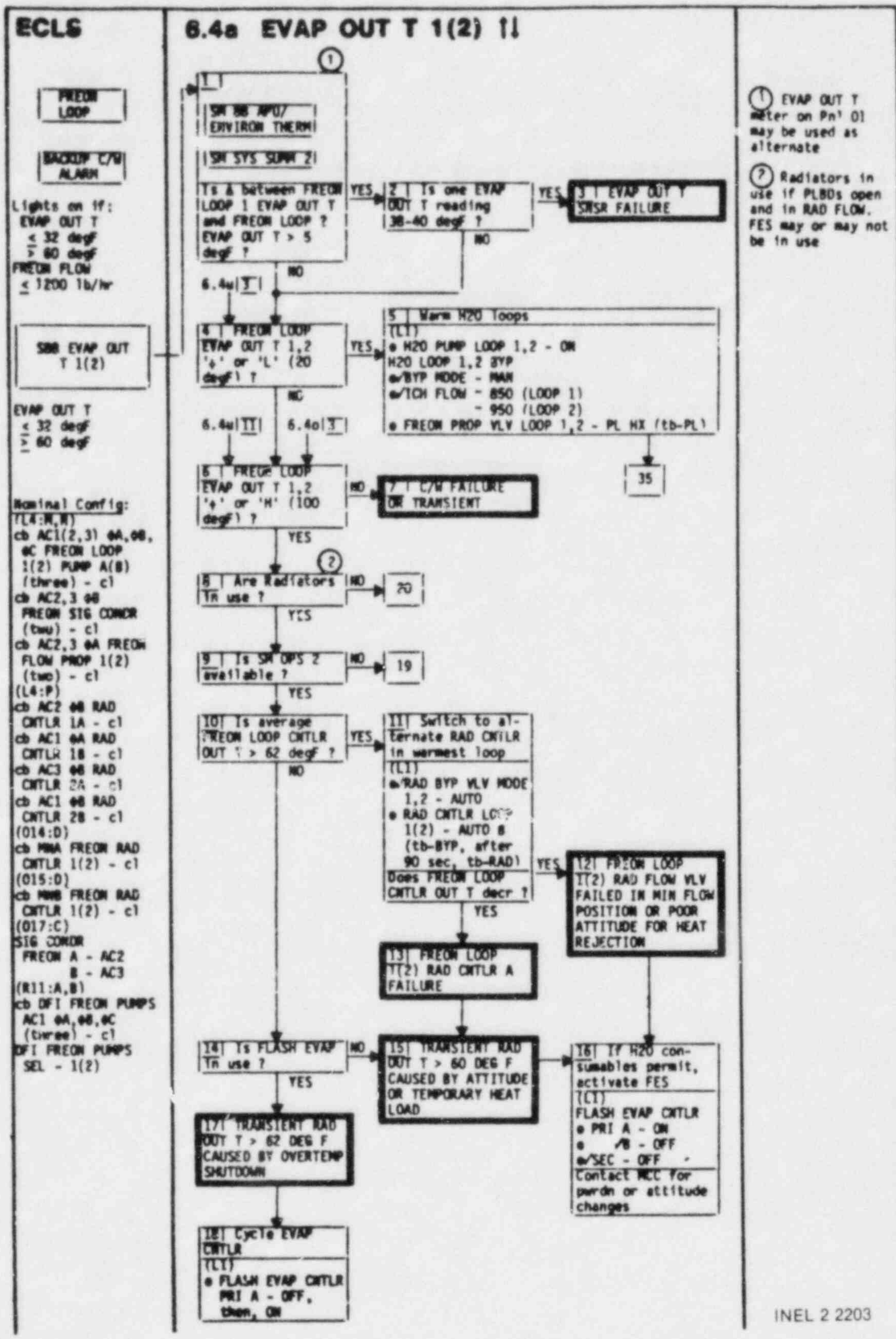


Figure 12. Excerpt from NASA malfunction procedures.[11]

Table 3. Guidelines for standardizing alerting functions and methods[25]

Condition	Criteria	Visual	Aural	Tactile
Warning	Emergency operational or aircraft system conditions that require *immediate* corrective or compensatory crew action	Centrally located alphanumeric readout (red)	Attention-getting tone plus voice[a]	Stick shaker (if required)
Caution	Abnormal operational or aircraft system conditions that require *immediate* crew *awareness* and require prompt corrective or compensatory crew action	Centrally located alphanumeric readout (amber/yellow)	Attention-getting tone plus voice[a]	None
Advisory	Operational or aircraft system conditions that require crew *awareness* and may require crew action	Centrally located alphanumeric readout (unique color)	Attention-getting tone	None
Information	Operational or aircraft system conditions that require cockpit indications, but not necessarily as part of the integrated warning system	Discrete lights (green and white)	None	None

a. Voice is optional.

Table 4. Aircraft alerting system master cue characteristics[25]

Variable	Concepts A and B
Visual	
Number	Two
Location	Near 15-degree cones
Flash	No
Brightness	15 to 150 fL
Size	1 degree
Cancellation logic	Manual and automatic
Duty cycle	NA
Color	Red, yellow
Verbal	
Number	Three
Signal-to-noise ratio	5 to 10 dB
Cancellation	Manual and automatic
Stereo type alerts	No
Duty cycle	NA
Spectral character	In guidelines
Location	90 degrees
Masking	Controlled via design

of a volume control that automatically adjusts the loudness so that the tone is always 5 to 10 dB above ambient noise, despite the fact that the noise levels may change.

Table 5 summarizes the CRT information display and verbal alert characteristics. The main differences between the two candidate concepts are the options available for voice alerts. In Concept A, only warnings are verbalized—automatically—and repeated until the crew cancels the warning when the problem is resolved. Concept B allows no or both warnings and cautions to be verbalized, but at the pilot's discretion. The CRT display shows a maximum of 12 alphanumeric messages that are arranged either chronologically or categorically (i.e., warnings, cautions, advisories) using a pushdown stack and coded in either red, amber, or blue. Each message line shows the locati[illegible]em name, and condition being annunciate[illegible] indicated alerts will be surrounded by a [illegible] box and a cue will advise the crew of page overflow (i.e., more than 12 alert messages). The pilot may remove and store all messages, except warnings, and recall them until the problem is resolved.

The aircraft alerting system identifies the problem and indicates its severity via the category of alert. It does not provide guidance for the crew members in corrective action. This study has much to offer the nuclear industry in both the results and techniques aspects. The idea of establishing basic criteria for alarm systems without dictating

Table 5. Aircraft alerting system visual and verbal display characteristics[25]

Variable	Concept A	Concept B
	Visual	
Location	Central display	—a
Format	Priority and chronological	—a
Overflow	Paging	—a
Store-recall	Yes, except for warnings	—a
Brightness	15 to 150 fL	—a
Cues and aids	Box, arrow, etc.	—a
Content	Short phrase (syntax)	—a
Character size	14 min	—a
Character spacing	7 min	—a
Legibility	In literature	—a
	Verbal	
Type	Warnings elective	Warnings and caution
Format	Phrase	—a
Model (M/F)	Female	—a
Inflection	Montone	—a
Masking	Controlled by design	—a
Repetition	Yes	—a
Cancellation	Manual	Manual switch
Content	Status	—a
Signal-to-noise ratio	5 to 10 dB	—a
Multiple alerts	In sequence with repetition	No
Store-recall	No	Yes
Spectral character	Guidelines	—a
Location	90 degrees	—a

a. Variable is identical for both concepts.

actual design is certainly laudable and the concepts can be easily transferred to nuclear applications. The results of the remaining phases should be anticipated with much enthusiasm. As of this writing, no formal report will be issued for Phase II. However, Reference 26 is the final report for Phase III of the Aircraft Alerting Systems Standardization Study.

ALTERNATIVES FOR ALPHANUMERIC ALARM SYSTEMS

An element of commonality in all five systems just surveyed is the existence, usually at the lowest level, of an alphanumeric display that provides the operator with various pieces of information. This coincides with what is found in nuclear power plants of varying degrees of sophistication. If a CRT is included in those systems, the minimum use is to display alarm data via alphanumeric text strings. Will this need for detailed data in alphanumeric format continue? If so, some serious questions should be asked. Figure 13 summarizes the various fields of information found in the five surveyed systems. Note that there is little similarity in the content of the message string. While, these represent five different applications, they are still addressing the same problem. Another common element is the existence of a pushdown stack where multiple messages are to be displayed. Is this the best technique, and if so, why? If not, what are the alternatives? The remainder of this study addresses some of these questions. Hopefully, the results will yield some answers and may be used to improve current and future alphanumeric alarm message displays.

Unanswered Questions

Given the existence of an alphanumeric alarm message display, the first question that needs answering is what information is necessary for the operator to respond to each event. In other words, what data do the operators feel they need at this level to take appropriate action. Once this is identified, one is faced with the problem of arrangement. Does it even matter that one field comes before another? Viewing a snapshot of an alarm CRT minutes or months later will not change its comprehensibility.

An equally important consideration is dynamics, because the alarm systems are designed for real-time response by the operator. Is there an optimum number of alarms per page that an operator can comprehend? The systems just surveyed had numbers of 22, 22, 1, 15, and 12, respectively. How are the alarms added to the list and, perhaps more importantly, how are they removed? Is it necessary to implicitly tell an operator that a condition has been corrected or can that be implied by simply removing the alarm? Is a reset function helpful? The next sections will address these static and dynamic issues.

Static Considerations

The variability of message content found in Figure 13 is typical of alarm systems, even with the same industry. Therefore, the search continued for an implied standard which should be reflected in alarm displays of different vendors. An informal comparison of the contents of various alarm system displays yielded little commonality. In fact, a total of 15 different information fields, used in various combinations, were identified. One can logically conclude that the question, at least in the near past, has been

MFTF LINE # | RESPONSE FIELD | EXCEPTION # | PRIN. SUBSYSTEM | DATE, TIME | DESCRIPTION

HALO TIME | IDENTIFICATION CODE | DESCRIPTION

DMA TYPE | LOCATION | REFERENCE | VALUE | CONTROL ROOM CONDITIONS

NASA CRT ID | FAULT TEXT | C/W INDICATOR | DETECTING CPC | FAULT TIME | # MSG

AIRCRAFT ALERTING LOCATION | NAME | CONDITION

INEL 2 2208

Figure 13. Summary of alphanumeric alarm message strings for surveyed systems.

overlooked. It is desirable to know which of the 15 identified fields are necessary and sufficient for adequate alarm response.

To determine the necessary fields, 21 experienced nuclear reactor operators were tested.[a] Seven of the subjects were from the Training and Nuclear Instrumentation and Control groups of the Nuclear Power Systems Group, Combustion Engineering, Incorporated. All had nuclear Navy training and commercial and/or engineering design experience. The remaining 14 subjects currently work as operators for the Loss-of-Fluid Test (LOFT) facility at the Idaho National Engineering Laboratory (INEL). The vast majority of the LOFT personnel also had Navy experience before joining INEL.

Fifteen information fields were taken from various commercial and developmental alarm systems, although no system contained all. These fields and their definitions are alphabetically listed in Table 6. The fields can be further grouped according to their functional categories, i.e., the type of questions answered by the field. The four functional categories are given in Table 7.

Each subject was given an instruction sheet describing the purpose of the test and an alphabetic listing of the fields and their definitions. After reading the instructions, the subjects were asked to complete three separate untimed tests using pencil and paper. Throughout they were asked to imagine themselves in the control room and think of what information they need to respond to an alarm. The first test (the Rank Order or RO test) asked for a ranked order of the fields according to the usefulness. A unique rank from 1 to 15 was to be assigned with 1 being the most useful. The second (the Paired Comparison or PC test) was a paired comparison of all possible (105) two-combinations of the fifteen fields, asking the subjects to choose the most useful of the two. The final test (the Weighting Test or WT test) asked the subjects to assign a weight 0 to 100 to each field according to usefulness In this last test, a weight of 100 indicated that it was the most useful and more than one field could have the same weight. The fields were listed in random sequence and the subjects were encouraged to refer back to the field definitions whenever necessary. This was facilitated by including the field number along with the field name on each test.

a. The information in this section was presented in a slightly different form at the 1980 Instrument Society of America International Conference.

Results. The RO test yielded direct orderings for each subject. A mean ordering, standard deviation and z-score for each field was computed for the entire sample as well as for the two identified groups (C-E/INEL). The PC test data consisted of frequency counts that were used to establish a rank order for individuals and a mean frequency, standard deviation and z-score, for the entire sample. The WT test data was also ranked for individuals and a mean weight, standard deviation and z-score computed. The z-score in all cases served as a mechanism for final ordering.

A Spearman ρ calculation was performed to determine the consistency of an individual between the three tests. The average correlation between the RO-PC, PC-WT, and RO-WT tests using individual rank orderings were 0.855, 0.904, and 0.816 ($\rho < 0.001$), respectively. This indicates consistent responses from the same subject in each of the tests. A Kendall coefficient of Concordance was used to determine the agreement between subjects in the RO test. For the entire sample of 21 subjects, this calculation yielded a $\chi^2 = 154$ ($\rho < 0.001$). A separate calculation was done for the 7 subjects from C-E ($\chi^2 = 60$, $\rho < 0.001$) and the 14 subjects from INEL, ($\chi^2 = 103$, $\rho < 0.001$). The results indicate good agreement between subjects within each facility group (i.e., C-E/INEL) and concordance for the entire sample as well. The average ranking for the C-E group was compared to that of the INEL group via an additional Spearman ρ and yielded a correlation of 0.876 ($\rho < 0.001$). The final average ordering for the RO test is shown in Table 8. The normalized mean frequencies and standard deviations for each field, determined by the PC tests are shown in Figure 14. The fields are listed in descending order of their means. Figure 15 presents the same data for the weighting test, also listed according to descending mean. For comparison purposes, the average z-scores for each test are given in Figure 16. This figure also reflects the average orderings for each test. A Kendall Coefficient of Concordance for the three tests yielded a $\chi^2 = 40.42$ ($\rho < 0.001$) to again confirm the agreement of responses across the tests.

Discussion. The correlation, both within and between subjects, lends a high degree of confidence to the results obtained. The results may

Table 6. Alarm information definitions

1.	Alarm Limits (LIM)	*All* possible set points which are associated with a given parameter in alarm (trip set points, Hi/Lo set points, etc.).
2.	Alarm Severity Indicator (SEV)	A simple designator that specifies which alarm limit set point has been violated (HiHi, Hi, Lo, LoLo).
3.	Current Point Value/State (CUR)	The actual value of the parameter that went into alarm (Pzr Pressure = 2500).
4.	Date of Occurrence (DATE)	The month, day, and year that the alarm occurred (2/24/78).
5.	Detector Numb (DET)	The P&ID identifier of the detector which measures the current value in alarm (PCDAXL03).
6	Engineering Units (UNIT)	Units associated with any displayed values (°F, gallons/minute, PSI).
7.	Major System Designator (MAJ)	Name of the major system of which the alarmed parameter is a part (Coolant Loop 1, CVCS).
8.	Point English Language Descriptor (ENG)	Name of the parameter in alarm (Pressurizer Pressure, Hot Leg Temperature).
9.	Point Identification Number (ID)	Number used to access the alarmed parameter from the computer (NCP103).
10.	Priority (PRI)	An indicator that reflects the importance of the parameter when alarmed (Priority 1, Priority 2).
11.	Quality Tag (QUA)	Computer generated indicator that reflects the confidence level of the instrument measuring the alarm (Out of Range, Questionable).
12.	Reference (REF)	An indicator that tells the operator where he can find more information about the alarm (Display Page Number, Panel Containing Meter or Control).
13.	Sequential Number (SEQ)	A number that indicates the position of the alarmed parameter in the entire alarm list (No. 25).
14.	Time of Occurrence (TIME)	The hours, minutes, and seconds at which the parameter went into alarm (10:14:56).
15.	Violated Set Point (VIO)	The limit that has been violated to cause the parameter to go into alarm (Pzr Press Hi Limit = 2450).

Table 7. Information field functional category

Category A—What is in the alarm?

- Detector number (#5)
- Major system designator (#7)
- Point English language descriptor (#8)
- Point identification number (#9)

Category B—How serious is the alarm?

- Alarm severity indicator (#2)
- Current point/value state (#3)
- Violated set point limit (#15)

Category C—When did the alarm occur?

- Date of occurrence (#4)
- Sequential number (#13)
- Time of occurrence (#14)

Category D—Auxiliary information

- Alarm limits (#1)
- Engineering units (#6)
- Quality tag (#11)
- Reference (#12)

Table 8. Average rank order from RO test

1. Point English language descriptor
2. Current point value state
3. Violated set point limit
4. Alarm severity indicator
5. Engineering units
6. Priority
7. Major system designator
8. Alarm limit
9. Time of occurrence
10. Quality tag
11. Reference
12. Detector number
13. Point identification number
14. Sequential number
15. Date of occurrence

not be correct, but at least all the operators were applying essentially the same standard in ranking the fields under study. Furthermore, there appeared to be no difference between the judgments of the C-E group and the INEL group. The single failing of the study is that the results are valid only for the 15 fields used. There may be other fields, not included, that would change the resultant orderings.

The data in Figure 14 are interesting in that the operators definitely feel they need the Point English Language Description and the Current Point Value/State fields, and do not need the Date of Occurrence field. This is indicated by the high (or low) mean frequencies and the small standard deviations. The standard deviations of the values between these extremes show that little can be said about the necessity of the intermediate fields. Figure 15 confirms this conclusion with similar means and rankings, but with even larger standard deviations. This confusion is not at odds with the correlations previously mentioned. The operators agree on the relative rank orderings of the fields, but not the distance between orderings. In other words, the interval between two neighboring fields varies tremendously. Of the three tests used, the PC test, by nature of its design, has less bias and therefore the highest confidence level.

A quick comparison of the orderings in Figure 16 reveals a migration of certain fields over the three tests. Since the tests were conducted in the same sequence, one wonders whether a learning effect occurred. Given the definitions, the operators may have changed their opinions with increased familiarity of the definitions. Figure 17 illustrated this migration. The reference field moved up five positions in the orderings between the RO test and the WT test while alarm limits and engineering units

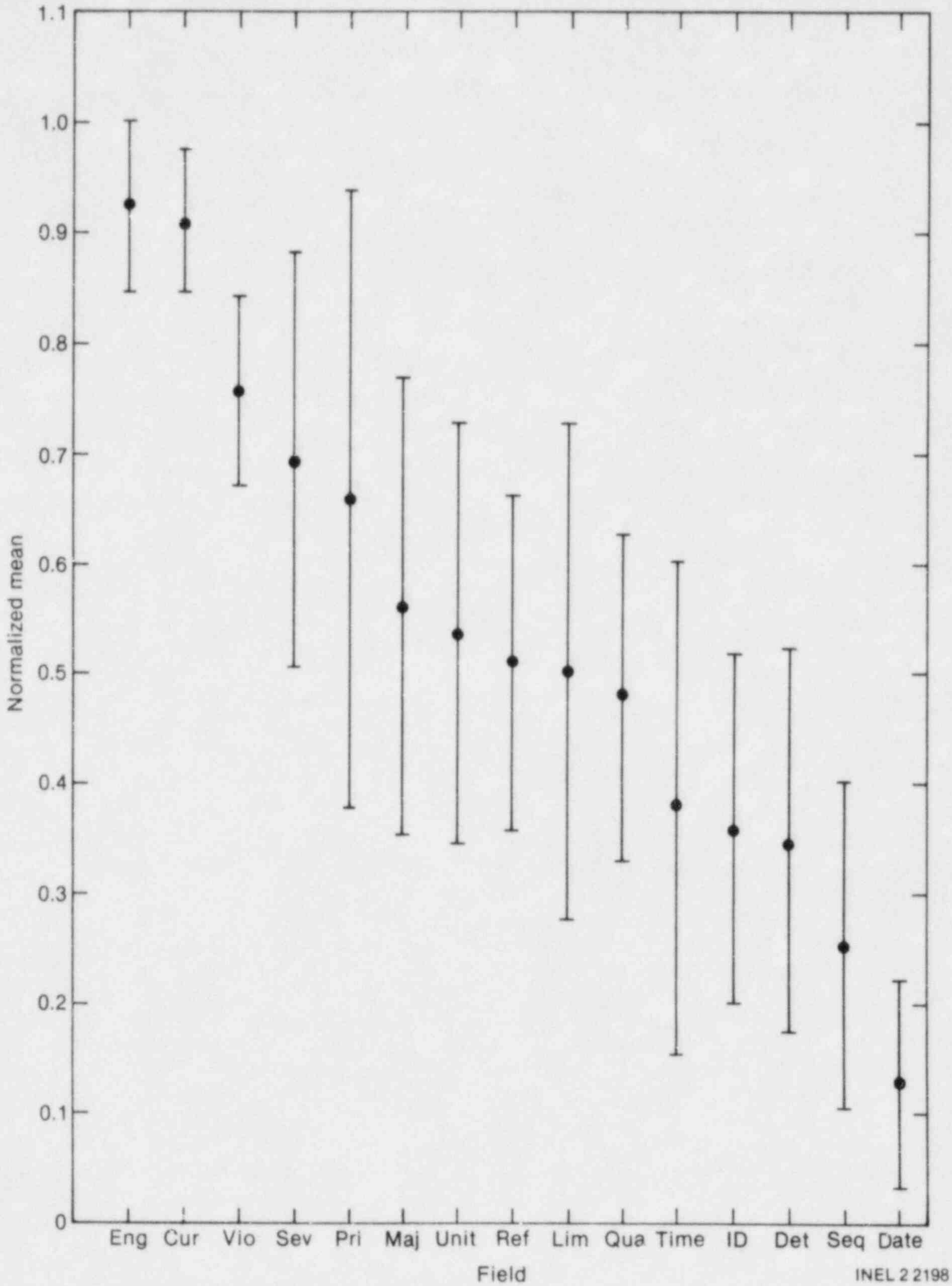


Figure 14. Paired comparison results.

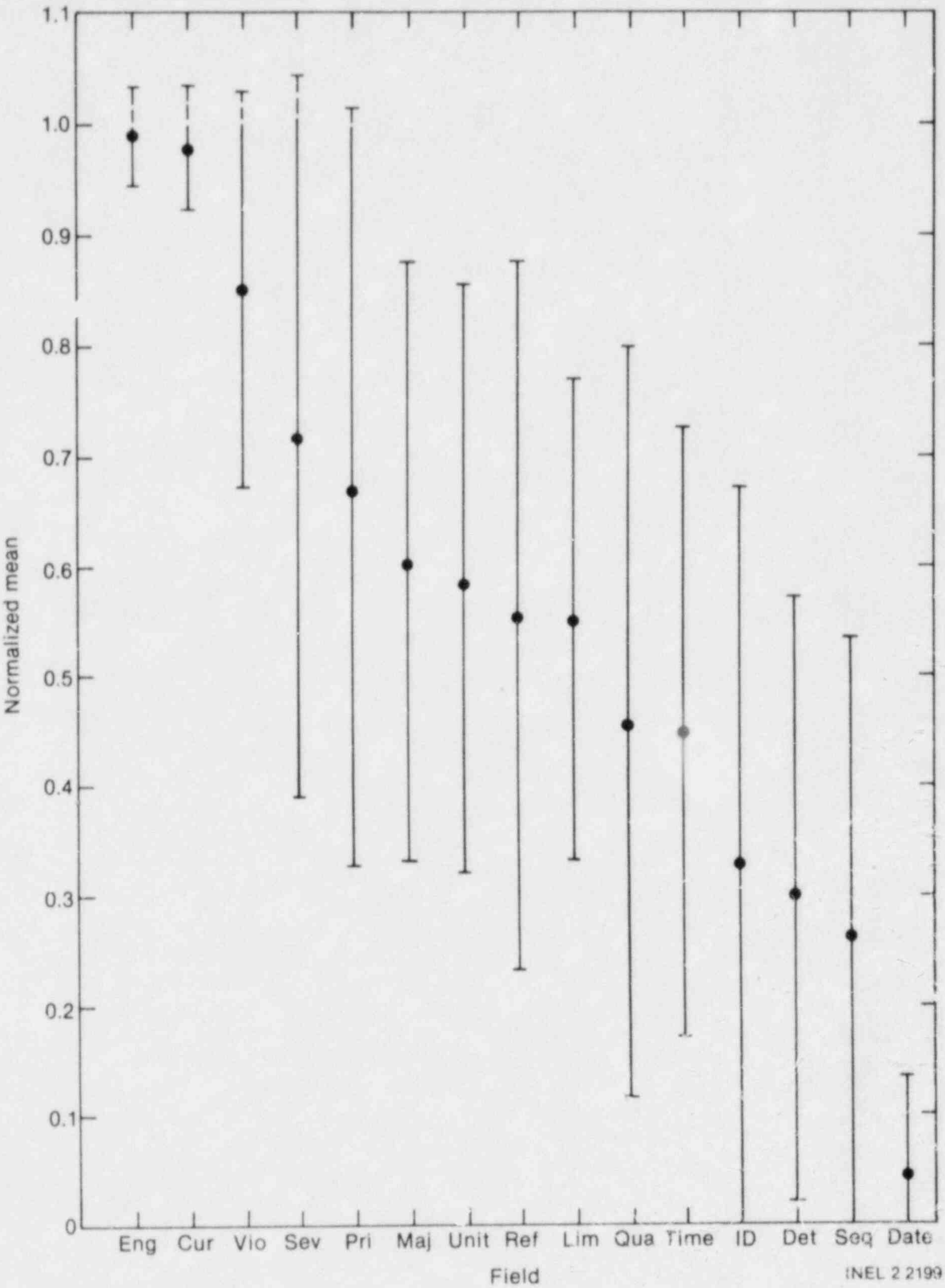


Figure 15. Weighting results.

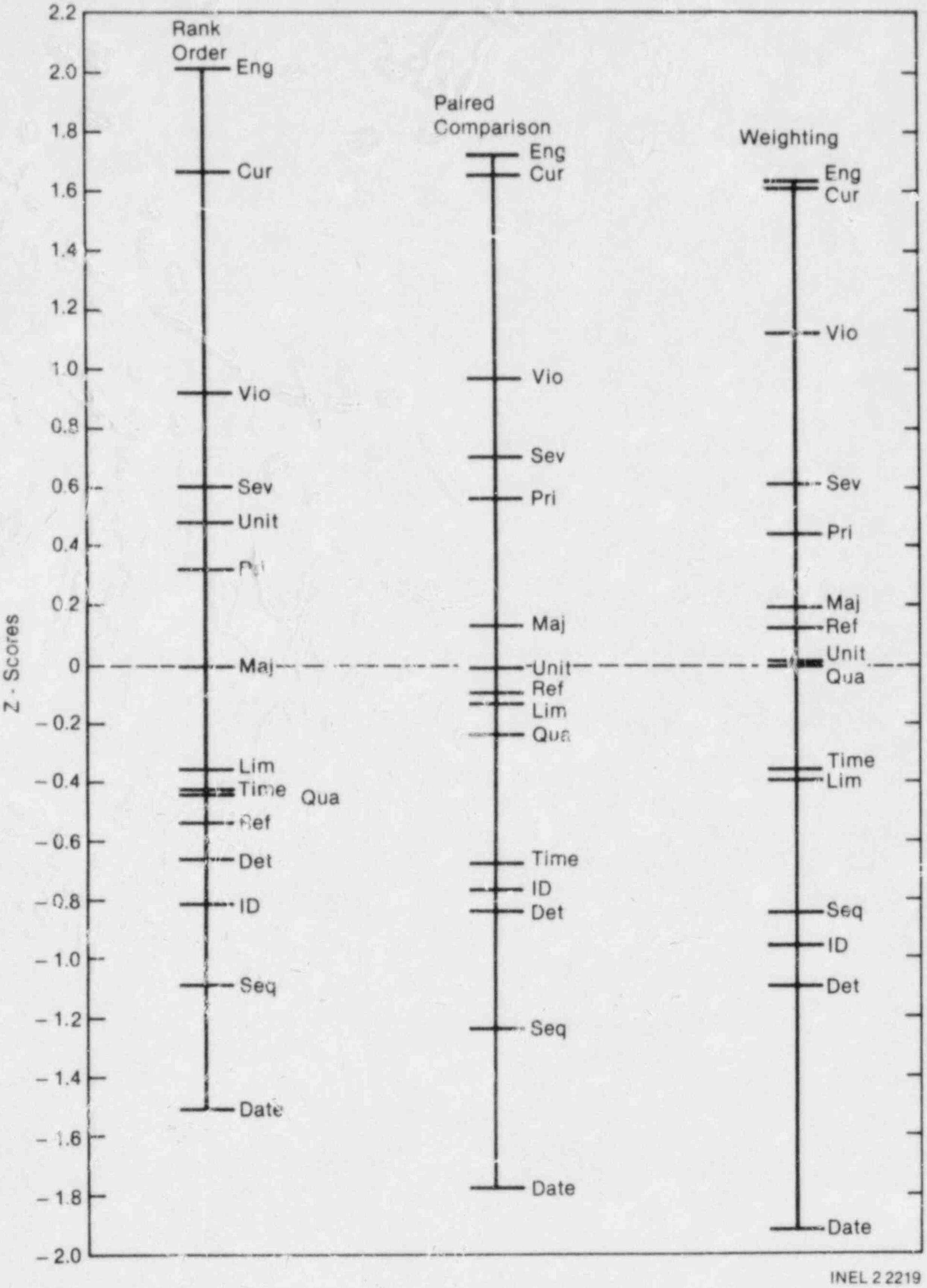


Figure 16. Comparison of ranks for three tests.

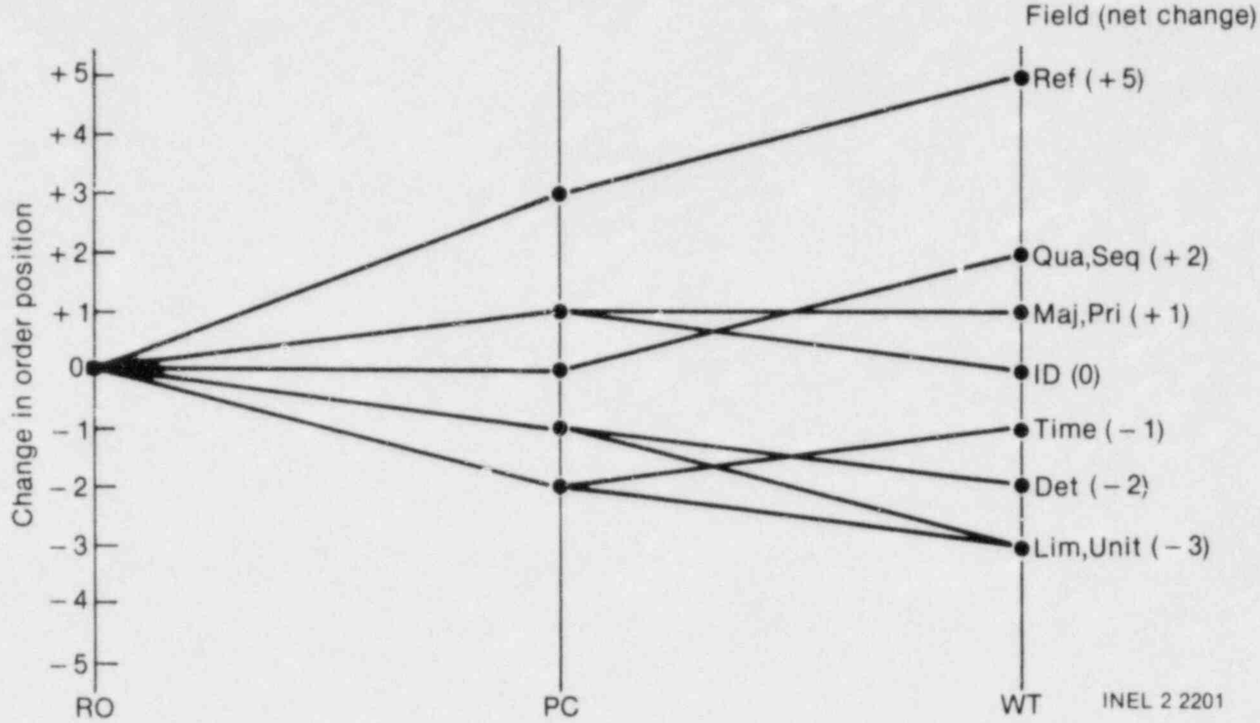


Figure 17. Migration of fields over three tests.

moved down three positions. This may reflect a change of opinion due to familiarity or an artifact of the tests themselves. Unfortunately, the sequence in which the three tests were conducted was not randomized in order to determine the reason.

The confusion noted in both the PC and WT results becomes particularly obvious if one uses the technique of partially ordered sets (POSETS) to evaluate different rank orderings of the same information.[27] Without this technique, the orderings from the three tests could not be merged into a single conclusion. Imagine two rank orderings of the following sequence: A, B C, D and A, C, B, D. The partial ordering rule states that one field is placed above another if and only if it is above it in all orderings. Hence, A is above all the elements (B, C, and D) and D is below all the elements. (A, B, and C) in both orderings. However, B and C must be placed on the same level, yielding a diamond-shaped figure. B and C are then said to be "not comparable."

This technique was applied to the three orderings of Figure 16, the results of which are shown in Figure 18. It is evident from the POSET that the operators all prefer the Point English Language Descriptor, Current Point Value State, Violated Set Point Limit and Alarm Severity Indicator, in that order in all three tests. The tests then yielded confusion, in that the remaining fields are not comparable until one reaches the Date of Occurrence field that was consistently ranked last. The POSET is a qualitative integrated display of all three rankings that provides information not otherwise available.

The indicated levels on the POSET provide an additional feature that can be combined with the quantitative z-scores of Figure 16. Following the technique of Reference 27, the product of the field's z-score, averaged over all three tests, and its level can be likened to a moment calculation where the level is the weight and the z-score the moment arm. This is shown in Figure 19, where the level is indicated by the height of the bar. A center of mass computation places the fulcrum at the point indicated. This figure implies that the usefulness of the 4 fields (ENG, CUR, VIO, and SEV) balances the usefulness of the remaining 11 and have a positive effect.

Further observation of Figure 19 reveals interesting data as to the type and amount of information the operator needs to respond to an alarm. ENG was functionally categorized as "What is an

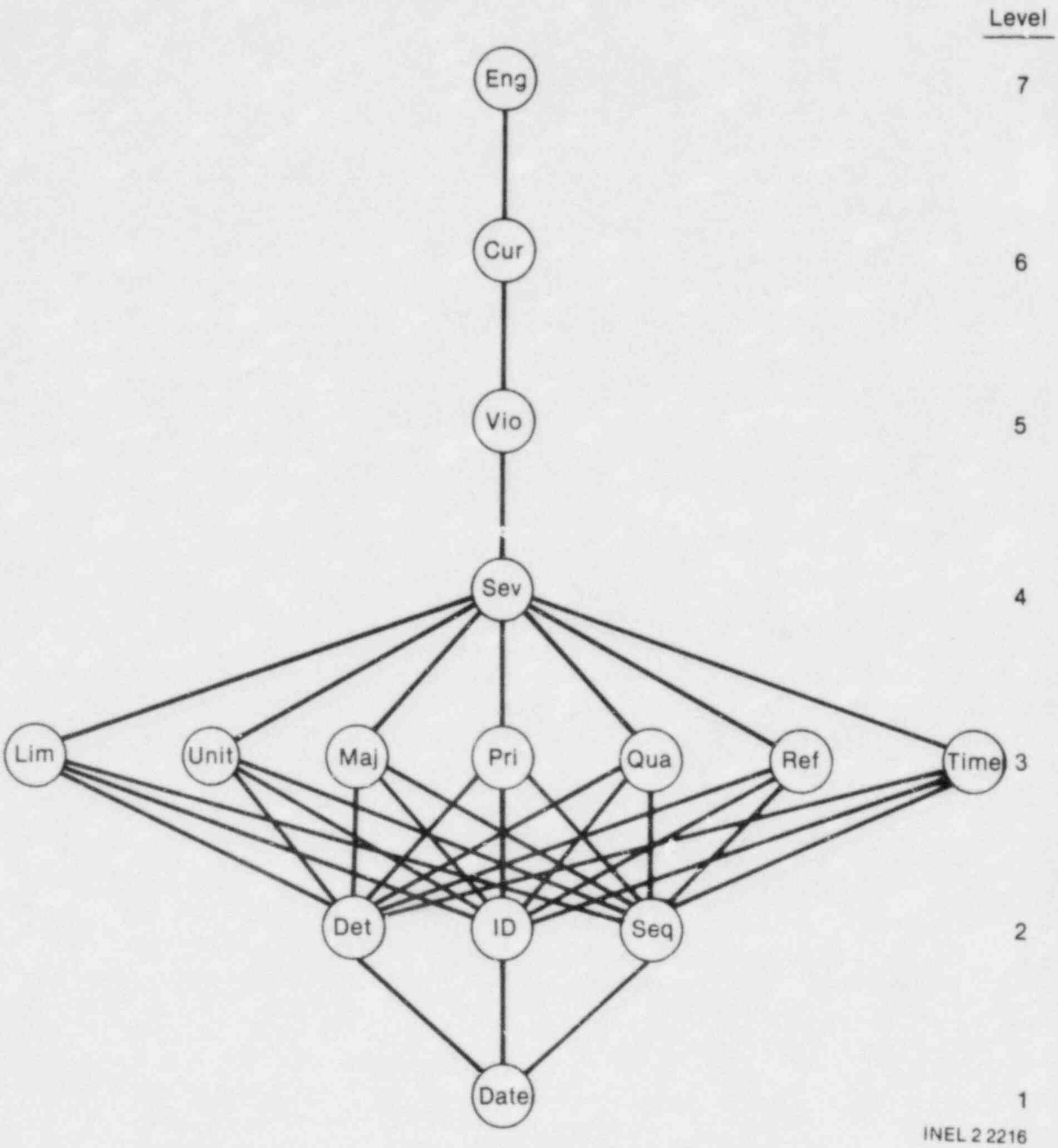


Figure 18. Partially ordered set (POSET) for ranking of Figure 3.

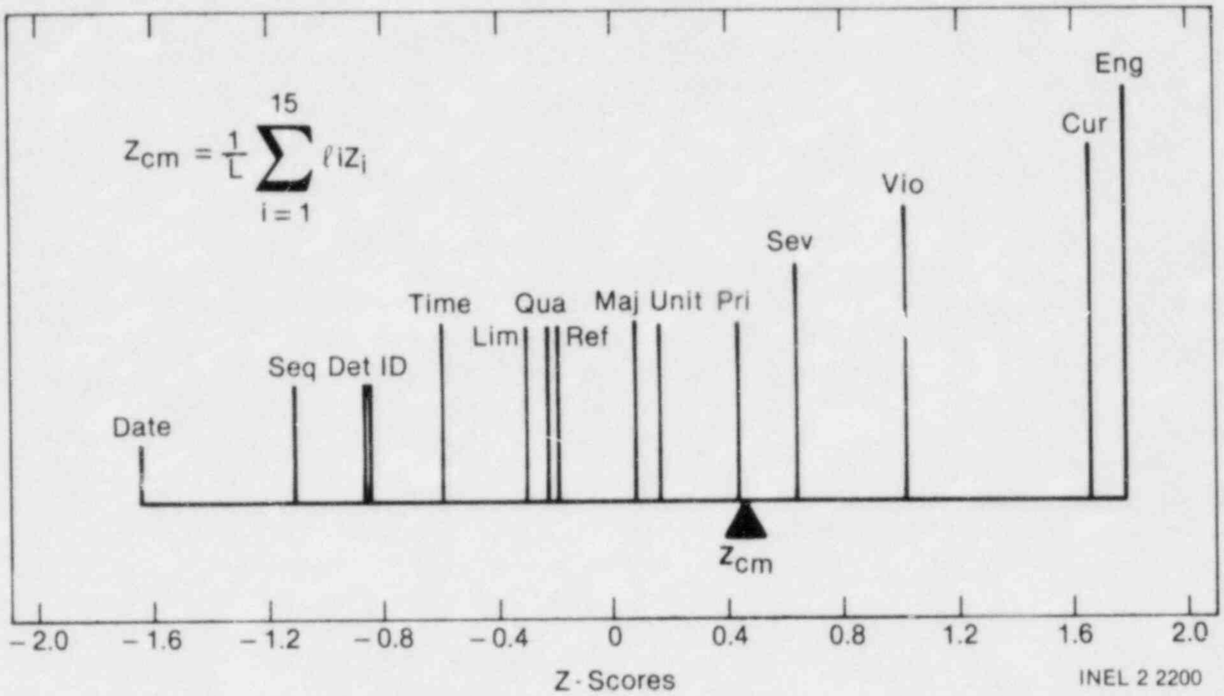


Figure 19. Moment arm calculation using Z scores and POSET level.

alarm?" in Table 7, while CUR, VIO, SEV, and PRI were all categorized as "How serious is the alarm?" One can conclude that the operators only need the point English language descriptor to tell them what the alarm is but want all available information related to seriousness. Presumably this reflects the operator's decision making process in that a good determination of severity will dictate his next action in responding to the alarm. The operators unequivocally stated that at least four fields of information were needed to respond to an alarm situation. Those fields are:

- A good English language descriptor of the problem (ENG)
- The current value of the parameter in alarm (CUR)
- The violated set point limit that triggered the alarm (VIO)
- A severity indicator such as HiHi or Lo (SEV).

A fifth field deemed desirable was priority, although operators were not sure how it could be determined. The operators rejected "date" as a necessary field of information. It must be emphasized that the operators in the survey were reflecting knowledge of existing systems that concentrate on alarms rather than conditions. However, it is doubtful that the basic requirements would change. Note that these fields reflect the first two functions of an alarm system. They identify the alarm and indicate its severity. In fact, the operators wanted as much data on severity as possible. Only a reference to corrective action is missing and could be explained by operator overconfidence in knowing what to do, given an adequate description of the problem.

Assuming that the results of the survey are valid, one is then faced with the problem of arrangement of the fields within the message string. Should ENG come first, followed by SEV, CUR, and VIO or should SEV come first? With four fields of data, there are 24 possible arrangements! Application of basic logic can reduce this total to six. The Current Value and Violated Set Point limit are closely related in that the difference between the two values indicates the severity of the violation. Since this is a comparison task for the operator, the optimum presentation is in tabular format,[28] the Current Value being placed on top of the Violated Set Point Limit.

The redefined fields are English language descriptor, Severity and Current Value/Violated Set Point. Two of the six possible arrangements are:

HIGH PRESSURIZER PRESSURE 2300
2250

or

2300 HIGH PRESSURIZER PRESSURE
2255

The first example reads as prose while the other provides quantitative information first. At this point it is tempting to pick the arrangement that "seems" more logical and deem it the best. However, performance is the crucial issue. Is there a measurable difference in how quickly or how well the operator can read any of these arrangements? That question will be addressed in the Performance Measures Section.

Display Dynamics

Display dynamics refers to the handling of multiple alarms in a real-time environment. Throughout the survey, mention was made of page capacity and overflow. A CRT is restricted to the number of messages that can be displayed on a screen at a given time. What happens when this number is exceeded? The survey also mentions a pushdown stack whereby the most recent alarm is added to the top and "pushes" the others down. Has this any effect on operator comprehension? When alarmed parameters return to normal they are usually removed from the CRT and the message list is reorganized. Does this have an impact?

An important fact to keep in mind when replacing annunciator windows with CRTs is that of display inertia. The position of an annunciator window is fixed in space. A trained operator, not overloaded, will respond to activation of that location without having to read the inscribed message. Such a display has much inertia because it never changes. A CRT is quite different in that it constantly changes. An operator has a mental picture of the contents of the alarm CRT and has to reestablish that picture every time an alarm message is added or deleted. The CRT can give more information, but tends to destroy inertia. The design of any CRT-based alarm message system must provide the required information while maintaining as much inertia as possible. Hence, one has three major factors to address: The number of alarms per page, how an alarm is added, and how it is deleted. This section will propose alternate methods for accomplishing each without trying to justify the superiority of one over another. That is a performance question that can only be answered by formal testing and evaluation.

The maximum number of alarm messages that can be physically (or electronically) placed on a CRT is determined by the resolution of the system and the character size used in generating the message. Standard alphanumeric video display terminals (VDTs) have 80 columns by 24 rows. Intuitively, one should not saturate the operator with 24 messages. The optimum number, less than the physical maximum, can only be found by testing. However, one would expect that even 24 is not a sufficient number to list all the alarms that may occur at one time. Therefore, a "backpage" capability must be assumed whereby alarms that are still in effect can overflow onto these pages but are still available to the operator.

Alarms may be added in the obvious pushdown stack fashion, although this discounts inertia. An alternate method is to fill the CRT from the bottom. New alarms are still at the top of the list, i.e., chronological, but the top is redefined each time. This maintains inertia until the page is filled, at which time a new solution is required. A third technique is similar to fill, except the bottom is redefined. This may be screen center, so the first message is half way down the screen and new alarms added on top. When the top half is filled, the contents are relocated to the bottom half and new alarms inserted in the top.

The alternatives for deletion have two major considerations. First, is an explicit RESET action necessary, and secondly, when does one rearrange the display? Some systems, such as MFTF, treat a return to normal as a change and notify the operator of that return. An operator action is then required to delete the message. Other systems, such as HALO, immediately remove the message on return to normal. Removal, or deletion, also detracts from display inertia in that the deletion is usually accompanied by a rearrangement of the message list. An alternative is to blank the message, leaving a hole, and removing that hole at some later time.

The Flexible CRT Alarm System

The flexible CRT alarm system is devised to include all the alternatives mentioned above for evaluation purposes. It is both a concept and a piece of actual software. The basic assumptions are the existence of a single color CRT and a keyboard for operator interaction. Through this keyboard, the operator may acknowledge new alarms, acknowledge return to normal (RESET) and request different alarm pages. The intent is to use this system to obtain quantitative performance data related to alphanumeric CRT alarm displays.

Table 9 lists the capabilities of this system. Five major factors may be tested, with a variety of levels available for each factor. Alarm messages may be displayed in the same color or in a maximum of seven different colors to indicate priority. A maximum of 14 messages may be displayed on a single CRT page, using the arrangements described previously. These alarm messages may be added to the display in three different ways and removed using the two techniques shown. RESET is a separate factor that works in conjunction with deletion. Any of these levels may be software selected at initialization to appropriately configure the system for the tests being conducted.

A set of alarm screen maneuvering rules was established to design the system and describe the workings. Some features are common to all the factor levels while others are employed only in certain configurations. The rules are shown in Table 10. The addition of a new alarm will be displayed in the appropriate color, with both flashing and an audible tone. The operator must acknowledge the new alarm(s) to halt the flashing. If a parameter changes severity, (i.e., LOLO, LO, HI, HIHI) but is still in alarm, the current condition is treated as a new alarm and the older one removed from the list.

Table 9. Flexible CRT alarm system capabilities

Factor	Level
Color	1 to 7 colors
Number of alarms/page	1 to 14
Addition methods	Pushdown Fillup Block mode
Reset	No/yes
Deletion	Immediate Delayed

The operator may request, via the keyboard, the next display page (backpage) in the set to view overflows or may request the first page that shows the most recent alarms. When changing pages, the alarm list is regrouped to fill the first page or bottom block. If new alarms occur while the operator is viewing a backpage, that backpage will be rearranged under the rules in effect. If the number of alarms is less than single page capacity and the operator requests "next page," the first page will be redisplayed. If the operator presses "next page" while viewing a backpage and there are no alarms in the list, the first page is displayed.

The Addition Rules describe the events on the first page for each addition level. Regardless of the addition method chosen, a chronological order is maintained and backpages follow the rules of the pushdown method. If pushdown is the addition technique selected, new alarms are added to the top of the CRT and existing messages are moved down or off that page. In the fillup technique the first alarm is placed at the bottom of the first page and subsequent alarms are added above it until the total number of alarms exceeds the specified capacity of the page. At this point, the pushdown technique is used until the total number of alarms is less than one page capacity. The block mode subdivides the first page into top and bottom blocks. The top block is filled from the bottom up. When filled, the top block is transferred to the bottom block and any "holes" are removed.

The Deletion Rules interact with RESET function. When reset is used and an alarm returns to normal, the color of the message is changed and retained on the screen until the operator presses "RESET." At this point the selected Deletion Rule becomes effective. Otherwise, the Deletion Rule is invoked when the parameter returns to normal. When immediate deletion is selected, the alarm is immediately removed from the list and the list is adjusted to be contiguous, i.e., no

Table 10. Alarm screen maneuvering rules for the flexible CRT alarm system

Common:

- Number of alarms/page set at initialization
- Number of priority colors set at initialization
- New alarms added in flashing, ACK stops flashing
- Realarm of parameter treated as new alarm
- Regroup alarm list on page change
- All backpages use pushdown stack method
- If new alarms occur while viewing backpage, adjust backpage
- If number of alarms is less than page capacity and next page is requested, display same page
- If last page is displayed and next page is requested, display first page

Addition:

- Pushdown—add new alarms to the top of the page, move others down or off the page
- Fillup—put first alarm at bottom, add subsequent alarms above it until the total number of alarms greater than page capacity. Revert to pushdown method until total number of alarms less than page capacity
- Block Mode—subdivide first page into top and bottom blocks. Fill top block from bottom up. When top is filled, shift top block to bottom, removing holes, and continue. On page changes, keep top block empty for new alarms

Reset:

- If RESET is in effect and parameters return to normal, make color cyan until operator presses RESET. Then invoke selected deletion rules

Deletion:

- Immediate—on return to normal or RESET remove message and adjust list to make continuous
- Delayed—on return to normal RESET, blank the message line. The hole may eventually be shifted off the currently viewed page or deleted via page change

"holes" allowed. With delayed deletion, the alarm message is blanked but the "hole" is not removed. The "hole" may eventually be shifted off the currently viewed page or deleted via a page change.

The hierarchical chart for the flexible CRT alarm system is shown in Figure 20. While not totally flexible, this system provides an easy way of testing the important factors in alphanumeric alarm displays. The experimenter initializes the system by selecting one level of each of the factors and then calls remaining functions as necessary, according to a test scenario. The system can be used to test alphanumeric CRT alarm displays in nuclear, aerospace, or other areas.

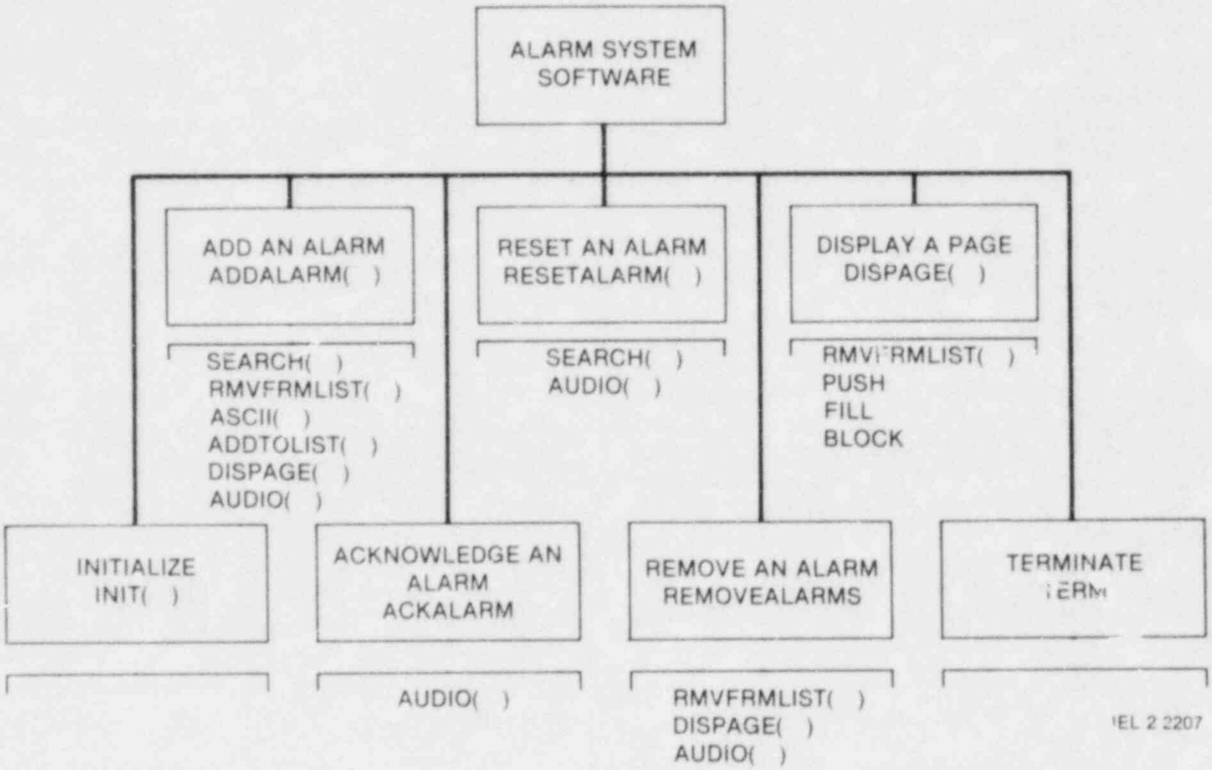


Figure 20. Hierarchical function chart for the flexible CRT alarm system.

PERFORMANCE MEASURES

The flexible CRT alarm system just described provides an alphanumeric alarm software package that alleviates the experimenter of intricate computer science details and allows concentration on evaluation. Although the package is generically written, the motivation for this study is nuclear process control. The ideal application of the alarm package would be installation in an operating plant as a stand-alone system and use trained operators for evaluation. Obviously this poses a multitude of problems from many aspects. The next logical application would be in nuclear simulators, still using experienced operators. However, training time is so limited and important that little time is left for experimentation.

The question facing every experimenter is the amount of fidelity necessary to measure basic performance. Is a full-blown simulation with the exact population required, or can lower fidelity experiments be devised? In this study, it was necessary to find a viable method for testing alphanumeric alarm displays under conditions that "simulate" those of nuclear power control, that is:

- The operator is very familiar with the process
- The operator is in a monitoring role
- A variety of alarms occur; some requiring immediate action, others requiring deferred action
- The operator must retain information over a period of time and make decisions appropriately.

Furthermore, the operators (or test subjects) must be readily available and relatively inexpensive.

A typical academic institution has a large pool of students that meet the last criterion, but fails totally in the crucial process control area. However, the Hartford Graduate Center is not a typical academic institution. Its students are usually working full time in area industries and pursuing master's degrees in computer and information science, engineering, and management in the evenings. Given this subject population, what type of experiment could be designed to meet the stated criteria? After much thought and many mistrials, a unique situation was found that may prove very interesting and valuable for display evaluation—that of a highly instrumented automobile. The instrumentation provided by automobile manufacturers is designed basically for warning. What does a low oil pressure warning light mean? Is a slight increase in coolant temperature critical or can it be explained by current conditions? The average driver usually assumes the worst case, but the knowledgeable driver can do much better. Imagine what is possible if the automobile was instrumented as in process control!

In both the Computer Science and Engineering departments, there are a substantial number of graduate engineers who are interested in and understand the workings of an automobile. They regularly read automotive magazines and comprehend the detailed specifications published therein. Hence, they are very familiar with the process. If one ignores the actual act of driving, the task becomes one of monitoring—monitoring the conditions of the road and the automobile. A variety of "alarms" are possible. Some are critical, such as brake pressure, while others are nuisances, such as the tire rotation indicator found on some automobiles. Furthermore, the driver must retain information on what has happened in the past and recall that information at some later time. For instance, a coolant thermostat that fails in the open position will cause the engine to approach operating temperature more slowly than designed. Not a cause for alarm, but it does require knowledge and understanding of past and current events.

The applicability of such a situation becomes more evident when the concept of "highly instrumented" is explained. Table 11 lists the instrumented parameters proposed, with associated set points. Given some freedom in how these would actually be implemented, the list has the flavor of a typical process control situation. If this technique proves viable, it may provide easy access to "operators" in order to gather quantitative data on the human decision-making process. Low-fidelity experiments may serve as the initial filter for display evaluation, assuming the results are later validated in higher fidelity studies.

Table 11. Instrumented parameters for the automotive examples

Alarmed Parameters

Number	English Language Descriptor	Set Points				Units
		LoLo	Lo	Hi	HiHi	
1	Left Front Brake Temperature	—	—	125	200	°F
2	Right Front Brake Temperature	—	—	125	200	°F
3	Left Rear Brake Temperature	—	—	125	200	°F
4	Right Rear Brake Temperature	—	—	125	200	°F
5	Left Front Brake Wear	—	—	x	x	
6	Right Front Brake Wear	—	—	x	x	
7	Left Rear Brake Wear	—	—	x	x	
8	Right Rear Brake Wear	—	—	x	x	
9	Brake System ΔP	x	x	x	x	
10	Brake Fluid Level 1	65	80	—	—	%
11	Brake Fluid Level 2	65	80	—	—	%
12	Coolant Level	50	70	—	—	%
13	Coolant Temperature	40	60	130	150	°F
14	Coolant Flow Rate	4	6	10	12	Gpm
15	Fuel Level	1	3	—	—	Gallons
16	Miles Per Gallon	20	23	—	—	MPG
17	Automobile Speed	—	—	57	65	Mph
18	Battery Charging Current	2	8	12	16	Amps
19	Battery Stored Charge	60	75	110	125	%
20	Ambient Temperature	-50	0	90	110	°F
21	Cockpit Temperature	20	32	80	90	°F
22	Left Front Tire Pressure	12	16	30	36	psi
23	Right Front Tire Pressure	12	16	30	36	psi
24	Left Rear Tire Pressure	12	16	30	36	psi
25	Right Rear Tire Pressure	12	16	30	36	psi
26	Left Front Tire Temperature	—	—	118	130	°F
27	Right Front Tire Temperature	—	—	118	130	°F
28	Left Rear Tire Temperature	—	—	118	130	°F
29	Right Rear Tire Temperature	—	—	118	130	°F
30	Tire Rotation	—	—	x	x	
31	Front Wheel Alignment	—	—	x	x	
32	Engine Oil Pressure	11	15	36	45	psi
33	Engine Oil Level	6	7	—	9	Qts.
34	Engine Oil Temperature	—	—	180	230	°F
35	Engine Oil Change	—	—	x	x	
36	Engine Oil Filter Change	—	—	x	x	
37	Engine RPM	1700	2000	4500	5000	RPM
38	Engine Timing	-10	-6	+4	+8	% Dwell

Display Arrangements

In the discussion of display alternatives, three information fields resulted from the application of logic: English Language Descriptor (ENG), Severity (SEV) and Current Value/Violated Set Point Limit (CUR/VIO). These fields may be placed in six possible arrangements, shown in Figure 21, with the automotive examples in Table 12. The first question the "simulated" process control situation, i.e., the highly instrumented automobile, should address is "is there any performance difference in the way the fields are arranged?" This is merely a reading and recall task and is not necessarily process control specific. However, in order to gain experience with the automotive example and the flexible CRT alarm system, a study was conducted using this problem. The null hypothesis is that there is no measurable performance difference between any of the six information field arrangements shown in Figure 21.

Method. Ten subjects were used, all of whom have a bachelor's degree in engineering and stated they have a more than average interest in automobiles. The group as a whole discussed the meanings of the alarmed parameters shown in Table 11. Each was given an instruction sheet and list of parameters to study before the test. The instructions and response forms are reproduced in Appendix A. The subjects were given the test three times, with approximately a two-week period between runs.

Figure 22 graphically illustrates the conduct of the experiment. The subject is seated at a VDT with a color CRT display to the left. They are instructed to watch the VDT and wait for an audible tone. At that time the subject is to look at the CRT display, where a single message in one of the six arrangements is displayed at screen center. They are to press the "carriage return" button on the terminal when they feel they understand the message. Both quickness and accuracy is stressed. The "carriage return" input blanks the CRT and waits for the subject to duplicate the message on a standard form, and then continues with the next alarm, triggered at random times. Before each run, the subject is given a trial run of five alarms and shown the correct results, Appendix A. Each test run entails 24 randomized alarm messages consisting of four different examples of the six possible arrangements. Response time and accuracy are recorded, as are posttest comments by the subject and the experimenter.

Results and Discussion. The results of the experiment are summarized in Figure 23. The collected response time data for each arrangement was collapsed and a mean response time and standard deviation computed. Accuracy was discarded, because error rates were virtually zero for all subjects. The figure shows mean response time and standard deviation for each run as well as an average response time and deviation over the three runs for each arrangement. The results are not statistically significant as determined by analysis of variance.

While not statistically significant, the data shown in Figure 23 point out an interesting trend. Over the three runs all response times improved, indicating a degree of learning by the subjects. Arrangement three (Table 12) is closest to prose but did not fare very well. The two fastest mean response times and smallest deviations are arrangements four and five, both of which have the qualitative data (Current Value/Violated Set Point Limit) before the English language descriptor. This response time result was reinforced by subject's comments and experimenter observations. In duplicating the alarm message on the response form, subjects tended to fill in the quantitative values first, and then the severity and descriptor text. Presumably it is easier to recognize the words than remember the numbers. This conclusion is supported by a psychological principle called the Serial Position Effect,[29] which states that in free recall of nonsense data, subjects more easily recall the beginning and ending data rather than the middle. In this experiment, the subjects did not need to read the entire English language descriptor, just enough to stimulate their memories, and therefore flattened the curve.

Experiment Conclusion. The results of this experiment and known psychological principles allow one to conclude that the more variable numeric data for Current Value/Violated Set Point Limit should come before the more easily remembered word descriptions. Although there may be hundreds of alarm descriptors, there can be many more possible values. In the terminology of information theory, the values have more "information" than the descriptors.

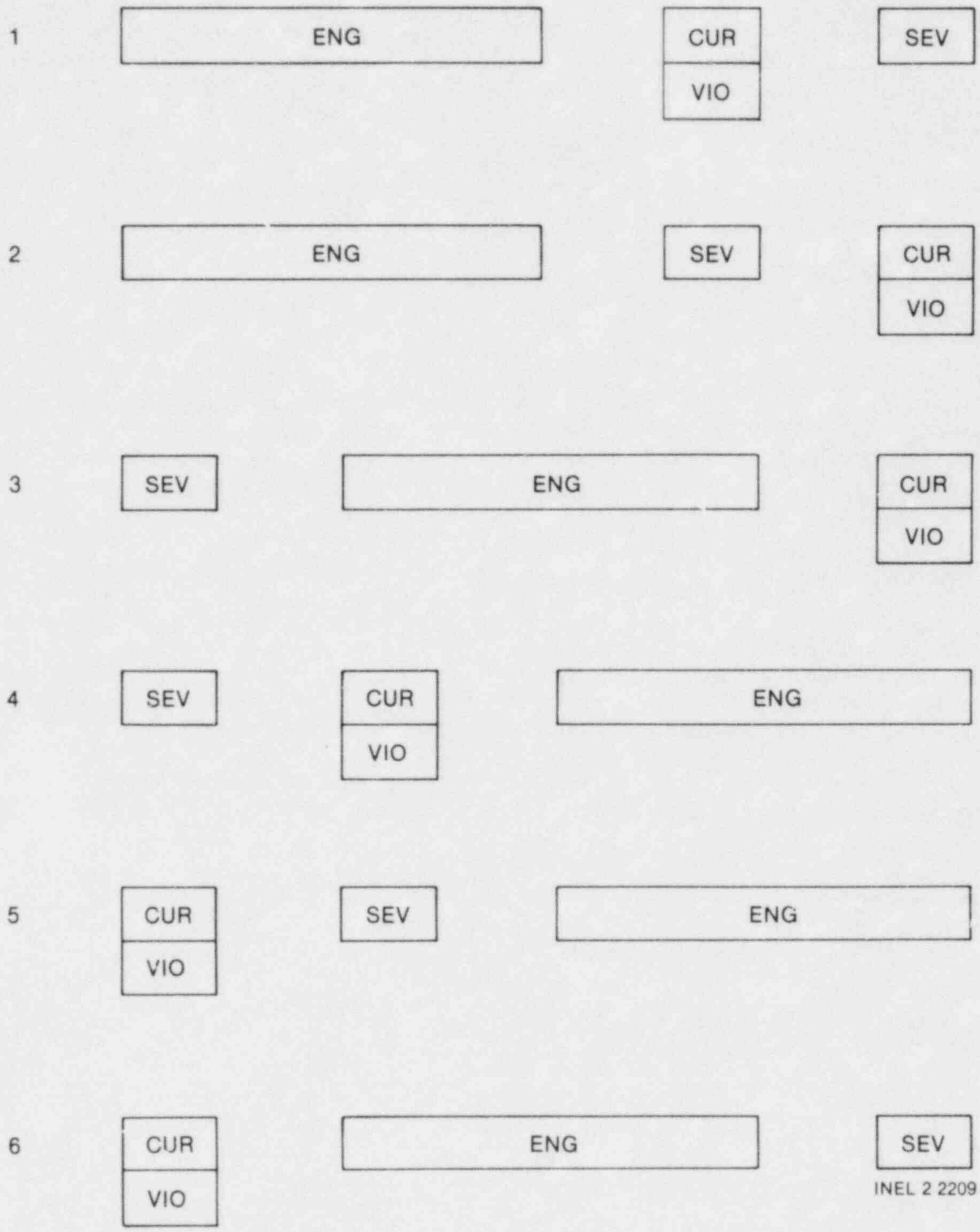


Figure 21. Six possible alarm field arrangements.

Table 12. Automotive examples of Figure 21

1.	ENGINE OIL PRESSURE	HI	40 36
2.	ENGINE OIL PRESSURE HI		40 36
3.	HI ENGINE OIL PRESSURE		40 36
4.	HI	40 36	ENGINE OIL PRESSURE
5.	40 36	HI ENGINE OIL PRESSURE	
6.	40 36	ENGINE OIL PRESSURE HI	

Display Dynamics

The true test of the automotive example and the flexible CRT alarm system is in dynamic situations that are beyond the scope of this study. However, some work was done to indicate how this might be accomplished. As illustrated in Figure 24, the alarm system is used in conjunction with a written scenario designed by the experimenter, much like the popular computer game "Adventure." The scenario is presented on the VDT in the form of lengthy text that must be read by the test subjects. The scenario establishes an environment for the test and focuses attention to ensure a monitoring task. At specified times in the scenario, an event occurs on the alarm display that requires operator identification and action. The action may be to ignore the problem, such as tire rotation, or take immediate corrective action. A sequence of events would be imbedded in the scenario to determine if the operator can come to a conclusion easier using different levels of the factors available. The performance should be reflected in response times, error rates and conclusions. An "expert" would determine the correct conclusions, given the available information.

An example of this concept is shown in Figure 25. This sequence of events should point to a brake failure due to a faulty caliper piston on the right rear wheel. Intertwined with this sequence would be unrelated nuisance and spurious alarms. These would mask the real problem, much like conditions in operating plants. A scenario would be overlayed onto the sequence to set the environment. For example, the scenario may describe driving up a mountain, viewing the scenery, etc. Brake failure is serious regardless of the conditions, but especially so in mountainous terrain where there are few alternatives. Hopefully tests like these may be conducted in the future to test the concept of low-fidelity experiments and their relation to nuclear process control alarm systems.

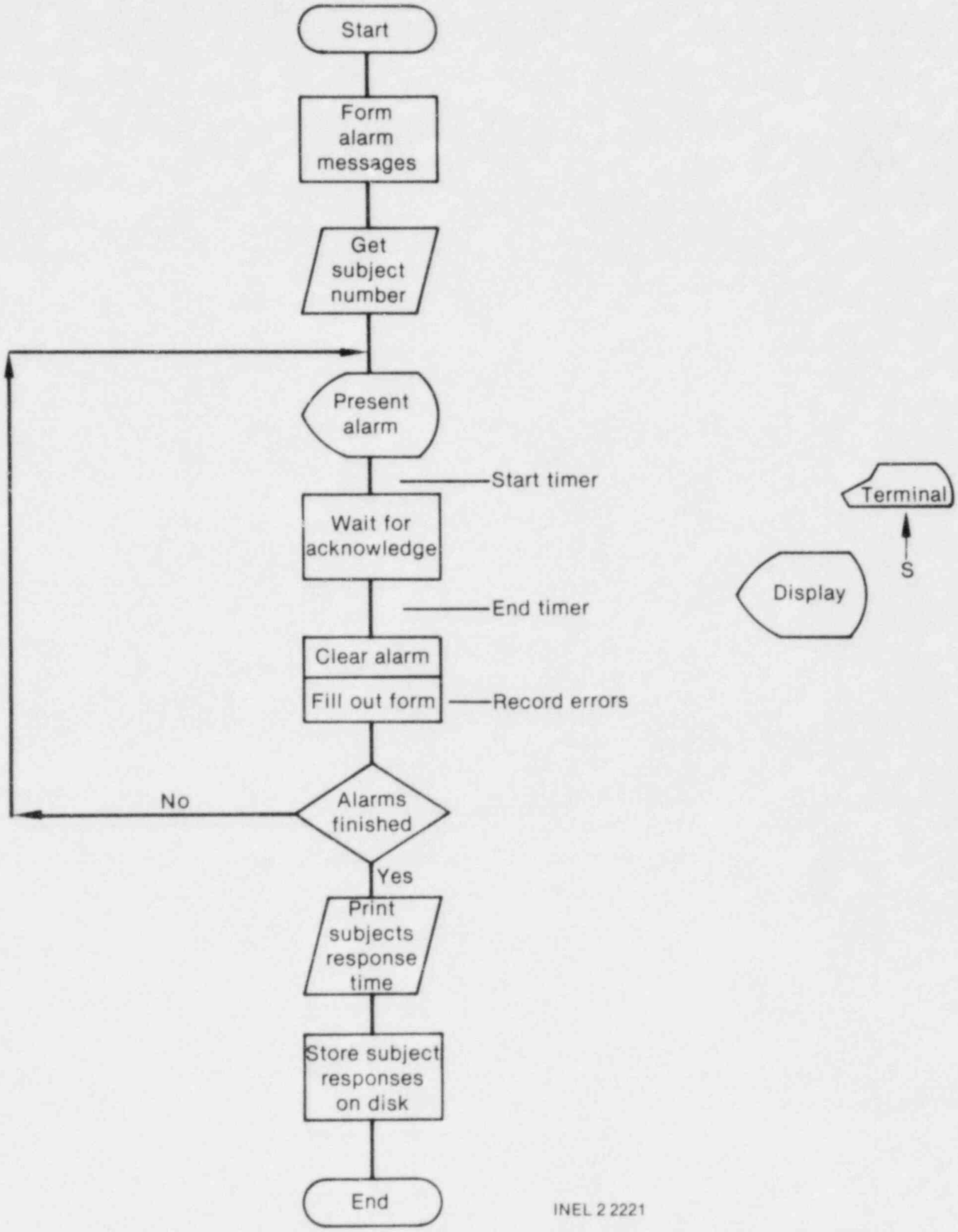


Figure 22. Test procedure for the single message alarm arrangement experiment.

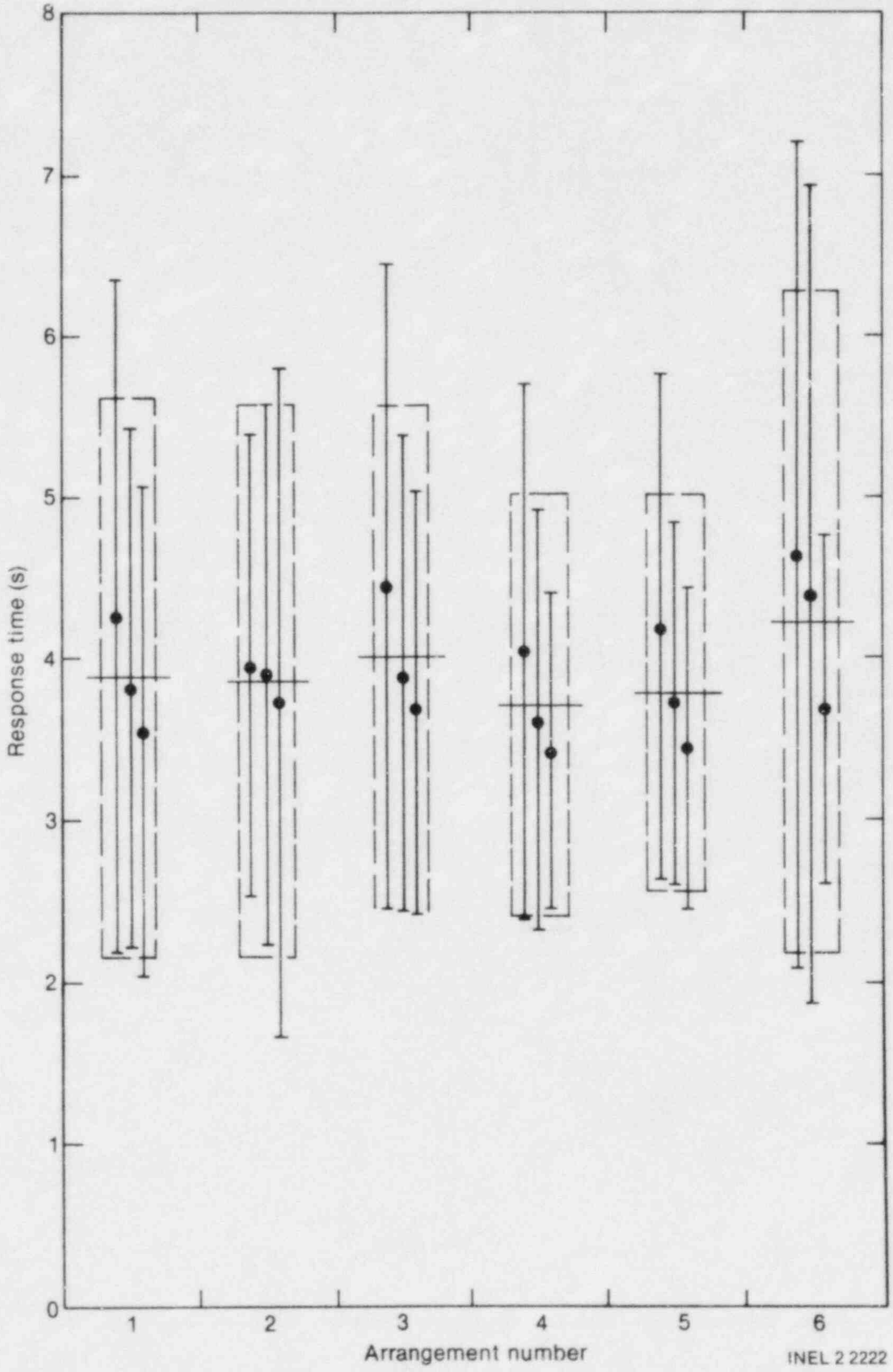


Figure 23. Results of the single message alarm arrangement experiment.

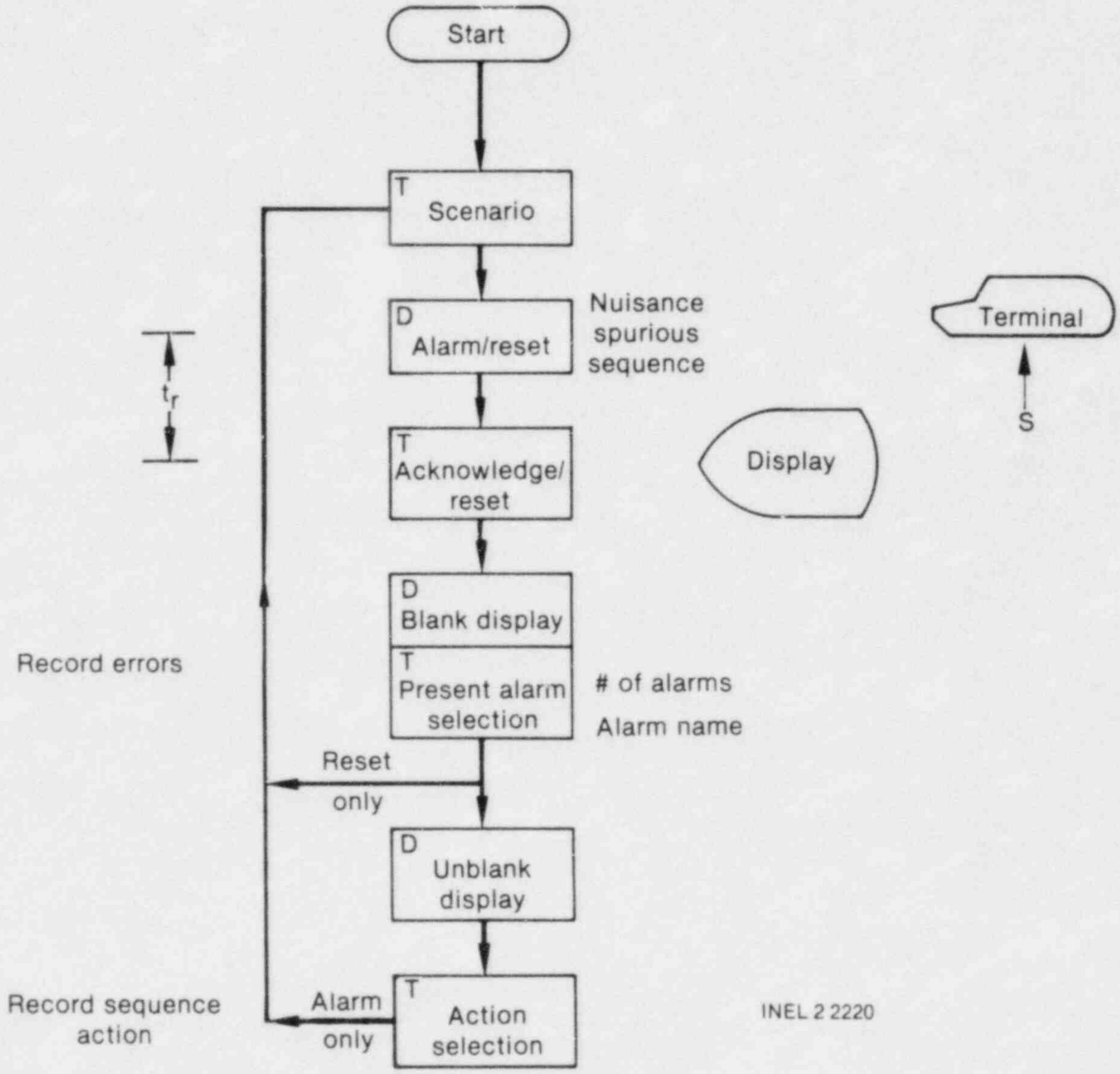


Figure 24. Test procedure for the display dynamics experiment.

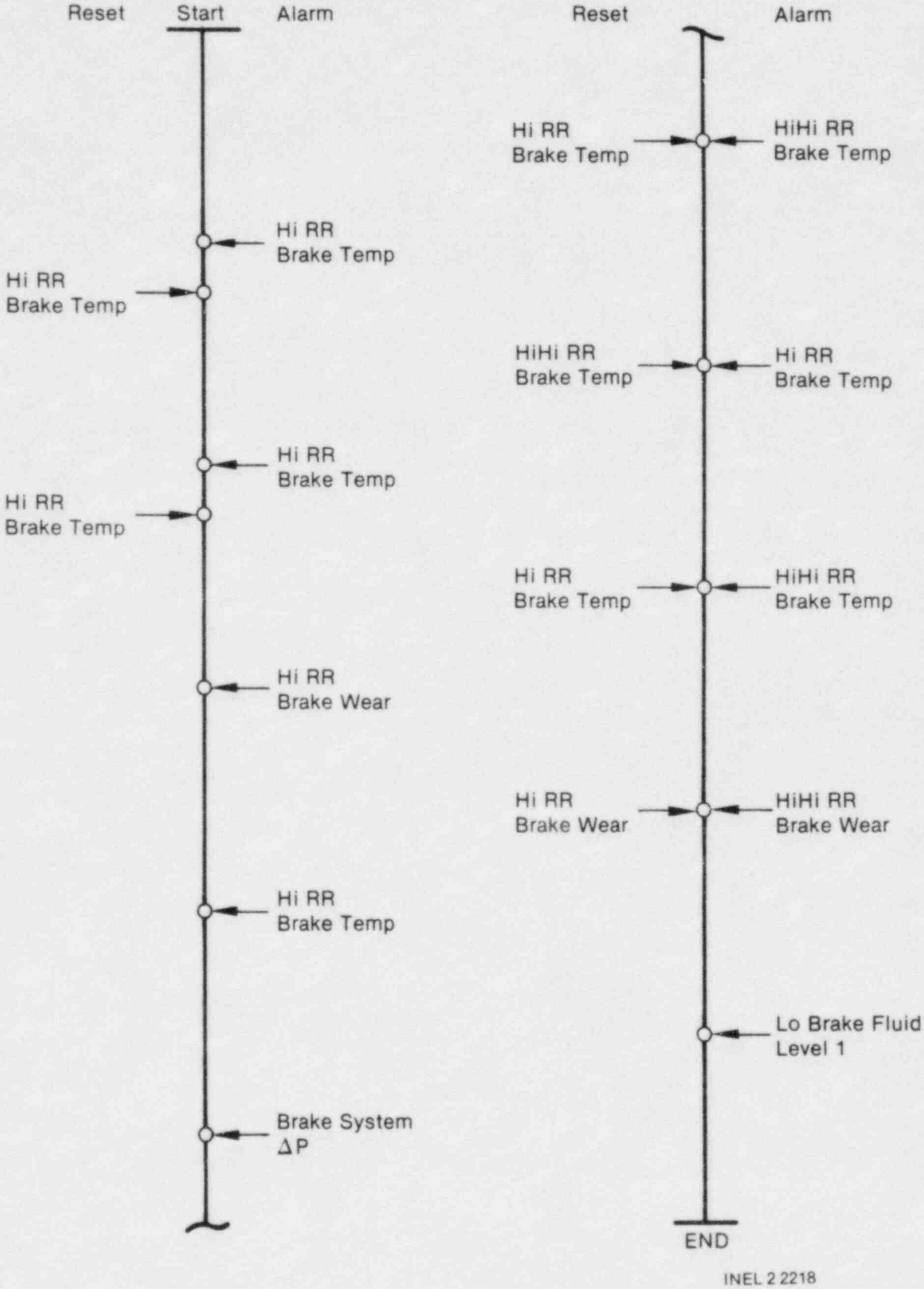


Figure 25. Sequence of events #1 for display dynamics experiment.

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion of this study is that a fundamental change in thinking is required in the area of alarm handling for nuclear power applications. The evolutionary process has left us with an "alarm" system, in the form of annunciator windows, that treats warnings, cautions, advisories, and information all on the same level. The systems surveyed in this study show a different approach in which conditions are alarmed rather than signals. They recognize different levels of annunciation and illustrate the caution and warning systems trends predicted by Thompson:[30]

- Soft rather than hard
- Information rich rather than simple
- Integrated rather than separated
- Assistive rather than nonassistive
- Intelligent rather than stupid.

The MFTF approach integrates the alarming function and makes interesting use of touch panels for operator interaction. HALO is a stand-alone system, but used groupings and hierarchy to identify the problem. The Savannah River DMA filters the inputs as much as possible and only annunciates the highest level leakage problem. Both aerospace examples use a master alarm and detailed message list. The NASA Space Shuttle keys and alarm message directly to operational data and corrective actions. The Aircraft Alerting Systems Standardization Study bases all its candidate systems on known and proven human factors principles and provides excellent recommendations for visual and aural cues.

A common factor in all the systems surveyed is the existence of an information-rich alphanumeric CRT display containing alarm message strings. Careful attention should be paid in determining the content of this message string and its arrangements. Low-fidelity experiments can "simulate" the real world of nuclear process control sufficiently and may provide a unique test bed for initial ideas in display layout.

The recommendations resulting from this study are obvious in retrospect. A simple change in terminology from alarm handling to "caution and warning" should provide a better philosophical goal for what is intended. Conditions should be annunciated, not signals. Persons in the nuclear industry should continually monitor the efforts in other areas to learn from their mistakes and successes. The different perspectives provided by these areas can lead to solutions never considered by the nuclear industry. The FAA study is an excellent example of a good human factors approach to a common problem and more people in the nuclear industry should become familiar with these efforts and results.

Furthermore, the alphanumeric message string will be an important part of any system and deserves more attention. Quantitative data should be presented first, followed by qualitative descriptions to aid the operator in the reading and recall tasks. More data is required on alternatives for display dynamics and how these alternatives affect operator performance. Low-fidelity experiments have a valuable role and should be used as a first step in display evaluation. Any type of evaluation, however, is much better than none!

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APPENDIX A
INSTRUCTIONS FOR CONDUCT OF TEST 1

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EG&G Test 1

Instructions. Previous experiments have indicated that process control operators need four pieces of information to adequately respond to an alarm situation. These are:

1. Name or English language descriptor
2. Severity indicator
3. Current value
4. Set point.

The name is just a clear description of the measured parameter and self evident. All parameters have a normal range of values, as shown in Figure 1. If the parameter value goes above or below this range, the parameter transcends the Hi or Lo set point and enters the HI or LO severity region, respectively. Further increases or decreases may cause it to violate the extreme HiHi or LoLo set points and enter those severity regions. The current value indicates the actual value of the parameter at the time of alarm. Table 1 lists the parameters and associated set points for this test.

Logic dictates that the current value should be placed above the violated set point to allow easy comparison. This reduces the total number of items to three. However, the question arises as to how the items are placed on a single line. An engine RPM value of 1900 (below the Lo set point) may be displayed in six possible permutations:

1.	Engine RPM	1900 2000	Lo
2.	Engine RPM	Lo	1900 2000
3.	Lo	Engine RPM	1900 2000
4.	Lo	1900 2000	Engine RPM
5.	1900 2000	Lo	Engine RPM
6.	1900 2000	Engine RPM	Lo

This experiment attempts to determine whether there is any significant difference between the six arrangements, i.e., is any one arrangement better than the others. This will be measured by response time and accuracy. You will be presented with a series of arrangements in which response time will be measured. Each alarm will be audibly annunciated by three tones. Only at that time should you look at the alarm CRT. Read the message and then acknowledge its receipt by pressing the "Return" key on the terminal, at which time the message will disappear. Do not press "Return" until you are reasonably sure of the message. After pressing "Return," record the message on the sheet provided. Then press "Return" again and prepare for the next message.

Remember, strive for both *speed and accuracy*. Do not press return until you are sure of the message and then record the message exactly as you remember it. You will be provided with trial runs before the data is recorded for analysis.

IF THERE ARE ANY QUESTIONS, PLEASE ASK!

EG&G TEST 1

INSTRUCTIONS

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4) setpoint.

The name is just a clear description of the measured parameter and self evident. All parameters have a normal range of values, as shown in Figure 1. If the parameter value goes above or below this range, the parameter transcends the Hi or Lo Setpoint and enters the HI or LO severity region, respectively. Further increases or decreases may caust it to violate the extreme HiHi or LoLo Setpoints and enter those severity regions. The current value indicates the actual value of the parameter at the time of alarm. Table 1 lists the parameters and associated setpoints for this test.

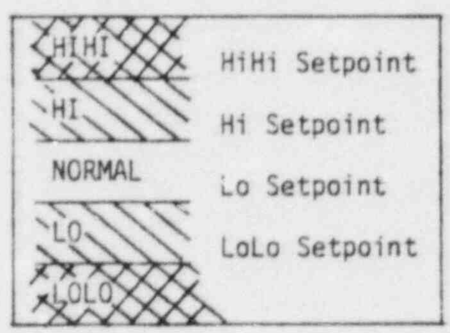

Figure 1

Logic dictates that the current value should be placed above the violated setpoint to allow easy comparison. This reduces the total number of items to three. However, the question arises as to how the items are placed on a single line. An engine RPM value of 1900 (below the Lo setpoint) may be displayed on 6 possible permutations:

EGGT1 EXPERIMENT
(TRIAL RUN)

Subject Number 100

ALARM NUMBER	NAME	SEVERITY	CURRENT VALUE/SET POINT
1	____________	___	______/______
2	____________	___	______/______
3	____________	___	______/______
4	____________	___	______/______
5	____________	___	______/______

2

ALARM NUMBER	NAME	SEVERITY	CURRENT VALUE/SET POINT
1	Engine Oil Pressure	Hi	40 / 36
2	Left Front Tire Pressure	LoLo	11 / 12
3	Battery Charging Current	Lo	7 / 8
4	Coolant Flow Rate	Lo	5 / 6
5	Engine Oil Pressure	Hi	38 / 36

EGGT1 EXPERIMENT

Subject Number ______________

ALARM NUMBER	NAME	SEVERITY	CURRENT VALUE/SET POINT
1	____________________	___	__________/__________
2	____________________	___	__________/__________
3	____________________	___	__________/__________
4	____________________	___	__________/__________
5	____________________	___	__________/__________
6	____________________	___	__________/__________
7	____________________	___	__________/__________
8	____________________	___	__________/__________
9	____________________	___	__________/__________
10	____________________	___	__________/__________
11	____________________	___	__________/__________
12	____________________	___	__________/__________

ALARM NUMBER	NAME	SEVERITY	CURRENT VALUE/SET POINT
13	____________________	___	__________/__________
14	____________________	___	__________/__________
15	____________________	___	__________/__________
16	____________________	___	__________/__________
17	____________________	___	__________/__________
18	____________________	___	__________/__________
19	____________________	___	__________/__________
20	____________________	___	__________/__________
21	____________________	___	__________/__________
22	____________________	___	__________/__________
23	____________________	___	__________/__________
24	____________________	___	__________/__________

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