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Performance of control room operators in alarm management

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PERFORMANCE OF CONTROL ROOM OPERATORS IN ALARM MANAGEMENT

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ABSTRACT

Pipelines transport millions of barrels of petroleum products every day. These systems have significant safety concerns. The BP oil spill in the Gulf of Mexico, while concerned with oil and gas extraction rather than distribution, shares many of the same safety and reliability issues as distribution systems, and demonstrates the significant potential for major disasters in the pipeline industry. In this work, a research study is being conducted to further understanding of the role of operators in the management of alarm systems and to measure the performance of operators in handling abnormal situations like pressure loss, liquid inflow/outflow variation and alarm floods. In an Abnormal Situation Management (ASM) consortium traditional interface study, improving the human machine interaction (HMI) in designing the operator's user interface resulted in 41% less time for the operators to deal with events like leaks, power failures, equipment malfunction and equipment failures in an unstable plant (Errington, 2005). To evaluate the impact of different alarm rates and interfaces on operator performance, a liquid pipeline simulation experiment of 1 hour was developed and the operators ran the experiment repeatedly at different alarm levels: chronological and categorical displays with the alarm rate of 15 alarms per 10 minutes (chronological display only), 20, 25 and 30 alarms per 10 minutes (the last rate with the categorical display only). Twenty five pipeline and refinery operators participated in this research, and the performance of operators was measured in terms of acknowledgement time, response time and the accuracy of response. Results showed that the operator's performance in terms of response time was significantly different between 25 and 30 alarm rates. Experiments to compare the response times in both the alarm windows did not show significant difference statistically, but the means were better in categorical display. This study will be useful in developing new standards on operator performance.

CHAPTER 1: INTRODUCTION

Petroleum products are often transported by pipelines and oil tankers. The largest volume products transported are oil and gasoline (petrol). The American Petroleum Institute (API) divides the petroleum industry into five sectors: Upstream, Downstream, Pipeline, Marine and Service & Supply. This work focuses primarily on downstream and pipeline systems.

Today there is a major concern for liquid and gas pipeline safety, and measures have been taken to understand the role of the human operator in the alarm management system to ensure the safe transportation of hazardous liquids. Supervisory Control and Data Acquisition (SCADA) systems are used to collect data from pipeline sensors and human controllers monitor the data from remote sites for operational and safety problems. The petroleum industry has lost billions of dollars in major pipeline accidents because of delays in finding problems and taking appropriate corrective action (NTSB, 2005). For example, in an accident in Chalk Point, Maryland where a pipeline ruptured at a buckle in the pipe, a leak was not noticed for 7 hours (NTSB, 2005). The safety board concluded that lack of adequate pipeline monitoring practices delayed discovery of the leak.

A study conducted in petrochemical and refining operations by Butikofer observed the sources attributed to cause of accidents include operator and maintenance errors (41%), equipment and design failures (41%), inadequate procedures (11%), inadequate or improper inspection (5%) and other (2%) (Formosa Plastics, 2007). Human errors can be caused by many variables, such as poor interface design, operator experience, communication problems, and shift fatigue.

In ASM's operator's interface study, correcting Human Machine Interaction (HMI) issues in designing the operator's interface resulted in 41% faster response to the abnormal situation

(Errington, 2005). Some of the HMI issues included color, alpha- numeric and text presentation, audible annunciation which should be well thought-out when designing the graphics display.

1.1 Problem Statement

The International Society of Automation (ISA) TR18.05-2010 standard (ISA, 2010) reports on alarm system monitoring, assessment, and auditing stated alarm performance metrics based on data collected over 30 days. According to the report, the maximum manageable alarms per hour per operator are around 12, and around 300 alarms per day and most of the required operator actions during an upset (unstable plant and required intervention of the human) are time critical. Information overflow and alarm flooding often confuse the operator, and important alarms may be missed because they are obscured by hundreds of other alarms. Operators usually work for 8, 10 or 12 hour shifts and concentration levels are unlikely to be the same throughout the entire shift. Alarm rates, operator interface design, fatigue and environment have impact on the operator's performance and his/her accuracy to respond to the situation. There is a need to design the alarm system considering human factors, so that the operator can always effectively keep focus on plant operations throughout the entire shift. Some of the issues encountered by operators include (Shahriari, 2006) :

- Lack of the optimum number of operators and insufficient screen space.
- External disturbances such as phone calls and the gathering of people around the control panel that may increase the confusion even more.
- Between various display modes, no overall standard is maintained leading to confusion in presentation, where messages and graphics vary from one computer display to another.
- No online help or guidance is available to assist the operators.

1.2 Objectives

The NTSB recommended improvement in alarm management, training and human machine interface design (NTSB, 2005). The design issues in alarm management include displaying the detailed information of where the problem is, and providing suggestive information to the operator in rectifying the problem.

The objectives of the thesis are to:

- Evaluate different alarm rates and its impact on operator performance (acknowledgement time, response time, accuracy of response, and successful completion). Accuracy of response evaluates the operator's ability to carry out corrective action in the correct sequence.
- Determine the effect of alarms displayed in categorical and chronological alarm displays on the operator's performance. Three experiments will use categorical display and another three experiments will use chronological display of alarms. Most of the petro chemical companies use chronological display of alarms, so in this project a comparison is made between the alarm displays for given alarm rates.

CHAPTER 2: LITERATURE REVIEW

2.1 Human Factors Analysis

In order to prevent accidents caused by human error in the pipeline industry, it is important to improve the safety measures in the operator's workplace and improve the effectiveness of human interface interaction. A good work environment will improve the operator's efficiency and the abnormal situations can be handled effectively. Eighty percent of the pipeline accidents are caused by human error as was noted in several studies conducted by ASM consortium, API and other similar organizations. Human error can be associated with poor operator interface design, operator experience, workload or shift fatigue, and lack of communication. Operators may not experience the same set of problems (like equipment failure, leak and power trip) whenever they have an abnormal situation and so it is important to accumulate the operator's knowledge from previously encountered abnormal situations in order to help the operator make a decision and avoid the wrong action for a known problem (Nimmo, 2002).

Operator must understand the characteristics of a process and adapt to the situation accordingly and it will definitely affect the safety of the control system. Operator's usability issues should be considered while designing the interface to improve their performance. The process designers are of the opinion that they can reduce or even eliminate the human error if they can, "remove human from the loop" and think of automation as the most convenient alternative for increasing system reliability (Meshkati, 2006). But according to meshkati, human operators will have to remain in charge to monitor and control the day-to-day operations despite the advancements in computer technology. Meshkati states that the reason is that the process designers cannot anticipate all possible scenarios of failure, and cannot automate the system to handle every possible abnormal event and they cannot provide pre-planned safety measures.

2.2 Interface Design

During emergency situation, the operator gets a lot of feedback from the SCADA system and the operator has to focus on so many variables at the same time. Figure 1 is an example of the LCD panels operators have to focus during emergency operations and it require a mental effort to sort, integrate, process through the available data to operate on plant situation (Nimmo, 2010). Nimmo states that the number of alarms we see in the process industry now is because of lack of leadership at that particular plant (Nimmo, 2011). Nimmo pointed out that while designing the alarms, process engineers specify process alarms, equipment engineers add up alarms for the protection of the machinery, control engineers specify the alarms while installing the distributed control system, operators point out some alarms based on how they felt using the HMI. In this process the number of alarms raised to 14000 DCS alarms (in general) from 140 physical alarms. Nimmo is of the opinion that the companies don't really understand the importance of alarm management until a disaster happens.

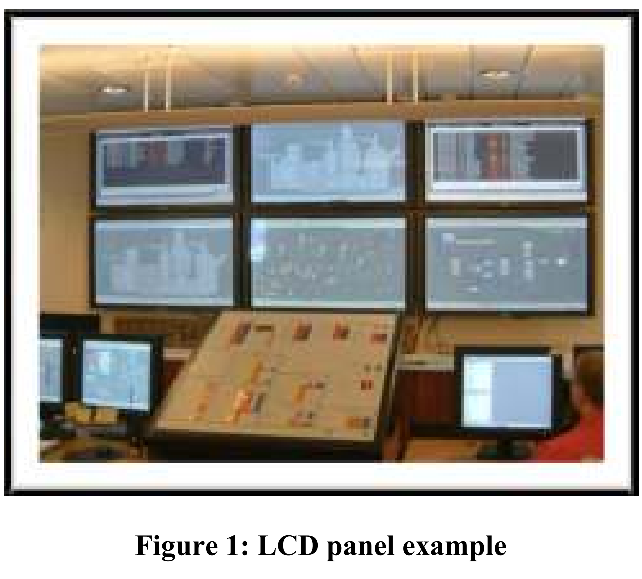


Figure 1: LCD panel example

2.2.1 Elements of the Interface

Many information processing technologies and new input-output devices, are now available in the commercial market and the invention of new types of human interface for supporting our daily work are developed (Preece, 2002). However, "the cognitive ability of humans has not varied, but is almost at the same level as that of prehistoric man" (Yoshikawa, 2003).

There are several issues while designing the Human Machine Interactions and few which have a direct impact include color, alpha- numeric and text presentation and quality of the audible, if provided (Errington, 2006). These issues should be well thought-out when designing the interface

'Direct manipulation' describes interactive systems where the user is provided with familiar methods of interaction (Preece, 2002). For example, the floppy icon we see in Microsoft Word is a common representation of a save option. The operator can easily understand and quickly find the object if its graphic representation closely resembles the physical world objects. In the operator's perspective, during emergency they must concentrate on many variables and if they cannot find the required tool or button quickly, the reaction times increase and can have a negative impact on decision making and taking action to prevent accidents or loss of production.

Some key recommendations of a graphical interface study conducted in the pipeline industry (Errington, 2006) include:

- Multi-windowing with controlled window management to minimize display overlays.
- Multi-level, simultaneous views of increasing plant detail.
- Automated display invocation through pre-configured display associations for assisted, task-relevant navigation.
- Tabbed navigation within a display level.

- Access to online information
- Limited color-coding, limited 3-D objects and simple/effective symbols

2.2.2 Degree of Fidelity

Graphical display and text console methods are available to interact with the operator interface (Preece, 2002). While designing the interface considering the above methods three specific details must be considered. They are:

- Operator's needs.
- Operator's goals.
- Operator's skills and knowledge.

An interface design should be operator centered and the information provided in the form of alarm messages and the control parameters defined should be easily understood by the operator. An easy navigation through the interface screens should be designed, so that the operator can manage and handle the workload during an emergency situation. The controls and devices whose data is monitored through the user interface can be designed to resemble the behavior of real world equipment and devices and it helps the operators to better understand the dynamics of the plant processes. A NTSB safety study conducted on 13 pipeline accidents from 1992 to 2004 concluded that some aspect of the SCADA system contributed to the severity of the accident in 10 of those accidents (NTSB, 2005).

2.3 Operator Training and Responsibilities

Operators handle many alarms which include nuisance alarms and information messages along with priority alarms. During an emergency situation, it is very difficult to predict where and when a pipeline accident may occur. Identifying an accident and to find the root causes for its propagation is a highly complex task (Meshkati, 2006). Training is essential to make the operators perform their jobs with proficiency and it helps to improve the plant production. Training should be given over a period of time in regular intervals and the training should be given in all scenarios the operator faces in real time (Bullemer, 1994). It's been stated in EEMUA No. 191 (EEMUA, 1999) that operators should be trained for detecting and diagnosing faults in the alarm system.

ASM conducted a study in 6 chemical plants to understand abnormal situation management (Bullemer, 1994). Information gathered from the plant incident reports to identify the initiating cause of incidents showed that there were not effective training programs to build the knowledge, skills and abilities of operations personnel. It was noted that the supervisors and field operators were not able to provide significant guidance to console operators. The authors stated that console operators expressed a need for more effective training and they also reported a feedback from the companies who expressed a reluctance to identify people as the initiating cause of an incident.

It is important to train and prepare the operators for infrequent events like leak detection in liquid pipeline. In order to improve the probability of operators finding the problem, along with on-the-job training, other methods should be designed and the safety study published by NTSB on SCADA system noted the importance of such practices (Christie, 2006). The author stated the mode of training the new hired operators have in the pipeline industries and also noted that operators do not learn any specific details of the pipeline because of their current training process.

2.4 Alarm Management

An alarm management challenge is to control nuisance alarms, alarm floods, alarms with wrong priority, and redundant alarms. EEMUA 191 metrics are shown in Table 1 (EEMUA, 1999).

Table 1: Metric provided by EEMUA 191

Alarm Condition	Benchmark value
Average alarm rate in steady operation	< 1 per 10 minutes
Alarms in 10 minutes after plant upset	< 10
Average process alarm rate	120 per day
Peak alarm rate per hour	15

By integrating a knowledge- based system into the alarm management system, it is possible to reduce nuisance alarms. This knowledge-base can be embedded into standard control modules that process the alarms and it is possible to manage the way alarms are presented to operators. For example, designers set alarms for low pressure, pump trip, and low flow rate for a pump. If the operator shuts down one pump in emergency, the alarms associated with that pump should be prevented from displaying on the screen. Ideally, alarms can be linked to a knowledge base system that isolates the root cause of the alarms and suggests corrective actions. With this approach there can be increase in the plant productivity and prevention of major accidents. The above approach helps the operator to concentrate on action required alarms and they are not distracted by all the information messages and nuisance alarms. This enables the operators to understand alarms quickly and can take immediate action on the required alarms.

A questionnaire survey was conducted for the Health and Safety Executive (HSE) in 13 process plants which include oil refineries, chemical plants, and power stations (Bransby, 1997). The above survey was conducted on 77 operators to determine the operators view on the alarm system from their perspective. The final report published by the study stated above found that the operators were not comfortable with alarm load and at times they received an excess of one alarm per minute. There were cases when the operators were flooded by 100 alarms in first 10 minutes after plant upset. Study stated that the operators felt distracted by the alarm flood which contains many nuisance alarms and so operators were used to give a minimum attention to these little operational value alarms and silence them in order to investigate them after the plant was stabilized. The authors noticed that in general, there were more problems with alarm systems in the plants equipped with modern computer based distributed control systems than some of the older plants which use individual alarm fascia. Some of the key observations made in this study are listed below (Bransby, 1998)

- It was noticed that only 6% of total alarms relate to active operational problems where immediate action is required.
- Around 50% of the alarms are repeated alarms, which were already acknowledged by the operator in the last 5 minutes.
- Most of the operators complained that the alarm flood was unmanageable during plant upsets and sometimes they accept the alarms without even reading and understanding them.

A survey conducted for the Health and Safety Executive (HSE) stated above described a strategy followed by one oil refinery they have visited in order to improve alarm management. The steps they have followed can be tried by other process industries to manage the alarm floods. The refinery tried to analyze one month alarm log to find the top ten nuisance alarms, recurring alarms which were noticed 500 times during that month and the standing alarms (Bransby, 1998). Based on the data, the company has tried to prioritize the alarms by having preliminary review of alarms by groups of two operators who have given them a provisional priority. Of all the prioritized alarms, operators reviewed the emergency alarms are re-categorized into lower priority. The above process continued till all the alarms were given the priority that was determined fine for the plant production.

The U.S Nuclear Regulatory Commission (USNRC) conducted a study to understand the human factor problems associated with power plant alarm systems (O'Hara, 1995). USNRC’s main objective was to develop guidelines for advanced alarm systems. These guidelines were developed considering the opinion of subject matter experts (SME’s) in power plant and human factors engineering. The factors these SME’s gave high priority are alarm processing techniques and alarm display issues. Alarm processing is required to filter the number of alarms and help the operator to work on operational value alarms and alarm display helps to prioritize the most significant alarms from low priority alarms. In this direction, O’Hara has illustrated the studies that have been developed to understand the effect of alarm processing techniques and alarm display strategies. For example, in a study to test the (Handling Alarms with Logic) alarm system, inexperienced students were asked to find the problems in a water reactor. They were trained with the system and the alarms were presented as unfiltered, filtered and filtered messages with an overview display. Results indicated that the accuracy improved by filtering the alarms. Similarly to test alarm display, a study was explained where alarm tile display, VDU display, and combination of both the displays were tested.

A study was conducted to evaluate the usability of a Safety Information and Alarm Panel (SIAP) on the operator performance in emergency situation (Norros, 2005). SIAP was designed with the purpose of providing operators with safety- relevant information and guiding them in decision making. The authors tested the impact of SIAP on process performance, crew working practices. The SIAP study considered 4 accident scenarios (2 scenarios with SIAP and 2 scenarios without SIAP) and 6 crew members participated in the study. The emergency situations tested were leak in a steam line, power failure etc. The scenarios were developed by considering the opinion of experts from the power plant. Results showed that there was no significant effect of SIAP on process performance, but showed different effect on crew's habit of action in different scenarios. Crew's habit of action was positive in some scenarios with SIAP and it was negative in other scenarios. The authors attempted to test new methods of improving the control rooms and similar tests can be done in other process industries and in this case pipeline industry.

Woods described the cognitive activities involved in dynamic fault management by taking the results of field studies from domains like commercial aviation, process controls etc. (Woods, 1995). Process status changes with time and fault management is the mechanism through which these changes are monitored to see if there is any disturbance in the process defined limits. Author explained directed attention, a cognitive function through which several techniques for developing effective alarm systems was explained. Nuisance alarms, unspecified alarm messages, alarm inflation and few others contribute to the difficulties that we find in alarm systems fault management. Woods explained 'Directed Attention' and 'Preattentive Reference' considering the case studies from the process industry to explain the fault management. Directed attention is a kind of coordination across process monitor agents where one agent can direct the focus of other monitor agents to particular conditions, events in the monitor process. Preattentive reference is also a cognitive process and it's about how the characteristics of the alarm systems are available to the controller in dynamic situations.

2.5 Operator Workload

An investigation at Scanraff oil refinery showed that during normal operation "the average number of operator actions per hour was 3.1 (a random week) and in upset conditions, the average number of actions per hour increased to 52.8" (Mattiasson, 1999). This means that the operator has to take almost 1 action per minute during plant unstable situation. Apart from alarms management, the operator has to convey the message over radio or telephone to the ground operator. This mental workload will have impact on the quality of the operator performance (Mattiasson, 1999). Information presented to the operator must be of a manageable magnitude, otherwise the risk of mistakes increases.

The mental workload of operators working in the pipeline control room is highly variable and according to Tikhomirov, high or unbalanced mental workload can have negative impact on the operator's performance. During an emergency situation, an operator may have a narrow span of attention on each alarm and they may forget the proper sequence of actions to be taken to solve a problem and it may result in them taking an incorrect evaluation of solutions, and effect their decisions. A study to observe the importance of human factors funded by the ASM Consortium showed that implementing human factors engineering into the design of an operator's graphical user interface (GUI) resulted in a 41% faster resolution of an abnormal situation as compared to utilizing a traditional interface (Errington, 2005).

Process control systems (PCS) optimize the plant operations in a safe manner. Operators depend entirely on PCS during normal plant condition and their workload is relatively low (Mattiasson, 1999). During abnormal plant situation PCS generates many alarms and the operator's workload increases. Over a period of time situation crosses the operator's limits to restore the system functionality and the alarm system will be less helpful to the operator. It is very important that the designers consider the operators workload during the interface design and build the system. Operator interface should not add additional workload during an emergency situation and should provide tools, recovery work procedures so that the operators have few constraints to maintain. During emergency situation, flow and level indicators will be unreliable and show false values due to pressure and/or temperature drop in various process streams (Mattiasson, 1999). Alarm system should monitor the process changes, because the alarm set points will remain those configured for normal operation and it will be difficult to the operator to analyze the alarm messages and take action.

In order to analyze operator's performance in plant abnormal conditions, a Boiling Water Reactor (BWR) nuclear plant in Japan used a full scale BWR plant simulator in their training center and data was collected on operator's responses to transients and accidents (Yoshimura, 1988). The authors have used on-line data collection systems and audio/video devices to gather the operator's data and data was used to analyze and identify the human errors and efforts were made to examine the contributing factors of those errors. In nuclear power plants, operators have heavy work load in feed water control systems, where they need to maintain the reactors cool and it was observed during experiments that when the operators were given the scenario of reactor scram, due to work load operators have done most of the errors. This example is to emphasize that work load effect on human performance and decision making.

2.6 Operator Performance

The operator's tasks change with changes in plant condition. If the plant is running without any hiccups, the operator's task is to optimize. When a minor upset occurs, the working conditions change and now the operators task is to bring the plant process to normal operational state. If there is a major upset, "the immediate task is to bring the plant to nearest safe state, and if disaster threatens, shut it down, and try to limit the consequences (Mattiasson, 1999)". To meet these expectations the operator must be provided with the tools necessary to carry out her/his duties to the best possible standard. There are many factors that can influence the operator performance and during an emergency situation, these factors play a key role on the operator's decision. Some of the factors that need a close attention are human machine interface, operator training, alarm systems, responsibilities and job design of the operator, environment, operator fatigue, communication procedures and alarm presentation.

The alarms presented to the operator should be relevant to plant situation and it is identified in today's alarm systems that the quality of information presented is not efficient and helpful to the extent the operator anticipated and having an impact on the operators performance. (Mattiasson, 1999). All the alarms are predefined conditions in typical alarm systems. But the process is dynamic and the operator has to adjust to the situation and deal with the process in order to get best results (Mattiasson, 1999). It's very important that an operator should identify the high priority alarms from the alarm list which are constantly rearranged and operator finds it difficult to search from the list which has changed, during emergency plant situations. Due to shuffle in the alarm list, the operator cannot focus on a particular alarm; if the alarm suddenly disappears from sight the operator must search to locate it. This search time consuming, and would be better spent on process recovery (Mattiasson, 1999).

2.6.1 Differences in Alarm Response and Acknowledgement Times

A set of experiments were conducted by (Uhack, 2010) to find the operator response times with different alarm rates. The response times were collected from 39 participants and using Tukey's mean test the difference was calculated. The author used both categorical and chronological display with the alarm rates of (1, 2, 5, 10, 20) alarms per 10 minutes. The results showed that for the 20 alarms per 10 minutes experiment there was a significant difference in participant reaction time between all other experimental alarm rates used. The author also performed an expanded Tukey's Means test for the interaction between alarm rate and alarm display type and results showed that, for the 20 alarms per 10 Min. experiment, there was a significant difference in participant reaction time between the categorical alarm window and chronological alarm window. The mean response times (in seconds) observed for the 20 alarms per 10 minutes experiment are as follows 112 (chronological alarm display) and 74 (categorical alarm display) (Uhack, 2010).

The above experiments also revealed data related to participant acknowledgement time. A Tukey's means test was performed on participant acknowledgement time with alarms displayed type and alarm rate. The results showed that, for the 20 alarms per 10 minutes experiment, there was a significant difference in participant acknowledgement time for low priority alarms between the categorical alarm window and chronological alarm window. The mean acknowledgement times (in seconds) observed for the 20 alarms per 10 minutes experiment, for low priority alarms only, are as follows: 191 (chronological alarm display) and 116 (categorical alarm display) (Uhack, 2010).

2.7 Standards and Regulations

2.7.1 CFR Part 192

Pipeline and Hazardous Materials Safety Administration (PHMSA) have made some changes with the federal pipeline safety regulations and according to new regulations in CFR part 192 (CFR, 2010); the pipeline industry management must develop control room management procedures by August 1, 2011 and implement those procedures by February 1, 2012. Some of these control room management procedures included are, to define rules and responsibilities of operators and the operators must be given proper training, necessary information and the management should design the methods to mitigate the operator's fatigue. Each operator is given on-the-job training and the management reviews the performance of these operators over a time and will periodically assess the operator's skills and knowledge through operator qualification (OQ) process (Nimmo, 2010).

2.7.2 ISO 11064

The ISO 11064 standard (http://www.iso.org/iso/home.html) guides the ergonomic design of control rooms and is divided into 7 parts. The standard states the principles in designing the control rooms and the principles for the arrangement of control suites. ISO11064-1:2000 deals with the principles for the design of control rooms. ISO11064-2:2000 provides principles of control suite arrangement. ISO11064-3:1999 provides guidance on control room layout issues. ISO11064-4:2004 provides guidance on workstation layout and dimensions. ISO11064-5:2008 provides guidance on displays and controls. ISO11064-6:2005 provides guidance on environmental requirements and ISO11064-7:2006 provides principles for the evaluation of control centers.

2.7.3 EEMUA 191

The EEMUA 191 standard (EEMUA, 1999) was first published in 1999 and has become the globally accepted and leading guide to good practice for alarm management. It gives comprehensive guidance on designing, managing and procuring an effective alarm system. Following the guidance in EEMUA 191 should result in better alarm systems that are more usable and that result in safer and more cost-efficient industrial operations. EEMUA 191 covers the aspects of alarm system life cycle and above standards deal with environment and human computer interaction issues.

2.8 Summary

The life cycle of alarm management plays a vital role in designing the safe and efficient SCADA system. Human errors cannot be eliminated, but can be reduced with good strategies implemented by the pipeline industries. By providing training, guidance and encouraging the operators can lead to improvement in their performance. By designing the control rooms around the operators requirements can reduce the physical and mental workload. By integrating the safety system and automation system as suggested by (Nimmo, 2010), designers can reduce the workspace the operator has to concentrate and with advanced technology, now it's possible to incorporate knowledge base into alarm systems so they can guide the operator to take corrective actions. Safety should be of high priority when the operator cannot control the situation and should shut down the plant if necessary. Previous experiments done by (Uhack, 2010) show that the operator reaction times increase with increase in alarm rates and it's been observed in his results that the operators tend to concentrate more on high priority alarms during emergencies. Standards like ISO 11064, EEMUA 191guide the designers and the operators in achieving what they intend to do.

CHAPTER 3: EXPERIMENTAL DESIGN

To evaluate the impact of different alarm rates and interfaces on operator performance, a within-subject repeated-measurement design was used to assess different alarm rates (15 per 10 minutes, 20 per 10 minutes) and different alarm display interfaces (chronological and categorical). A liquid pipeline simulation experiment of 1 hour was developed and the operators ran the experiment repeatedly at different levels: alarm rate (15, 20, and 25) alarms per 10 minute scenarios in chronological display and alarm rate (20, 25, and 30) alarms per 10 minute scenarios in categorical display

3.1 Experimental Apparatus

Advantica's Stoner Pipeline Simulator (SPS) is widely used in the pipeline community for engineering analysis and SPS was used to develop a pipeline model which calculates the fluid hydraulics and transients occurring in the simulated pipeline. Iconics Genesis-32 is an automation suite for developing OPC (Object Linking and Embedded (OLE) for Process Control) enabled Human Machine Interfaces for SCADA applications. For this project, GraphWorx32 and AlarmWorX32 was be used from the suite. GraphWorx32 is an HMI graphical display interface design package that was used to develop the graphical user interface (GUI) for the pipeline model. AlarmWorX32 is an alarm management system package used for handling alarm displays and it supports a backend database (Microsoft Access) to store the log data of all the changes happening in the simulation related to alarms.

Interface prototype screens were developed to be similar to the SCADA screens used for typical pipeline operations, and were shown to industry technical members to assess the face validity of the simulation during the design of experiment; the prototypes were approved by the industry technical members. The alarm rates and the complexity of the experiment were discussed with industry technical members prior to design. After the design of the experimental apparatus is completed, a pilot study has been conducted to evaluate the apparatus and experimental setup.

The experiment simulation consists of 2 pipelines (carrying diesel, gasoline, and crude oil), one from a rig and the other from a refinery. Each line has 10 stations as shown in (Figure 2). There is a detailed display for each station as shown in (Figure 3) and the operator can open all the stations simultaneously. In each station the operator can check the volume of the fluid and pressure maintained at each pump, and can use a block valve to maintain the steady flow of the liquid. The operator can start or stop pumps by right clicking the mouse button, and a window pops up to perform the operation. Each pump has suction and discharge valves, and a bypass valve. There are two tank farms, one at each end of the pipeline as shown in (Figure 2); their display is shown in (Figure 5) and (Figure 6). The inflow to the pipeline is circulated through a dehydrator (Figure 4) to remove water within the product in the pipeline. Each station has the hydraulic variation graph to show the pressure, standard flow and elevation.

Figure 2: Overview of pipeline stations

Two kinds of alarm displays were used to analyze the operator performance. The alarms were displayed either in categorical (Figure 7) or chronological (Figure 8) view based on the experimental condition. In the chronological display, the alarms are arranged in order of time of occurrence. For the categorical display alarms are grouped based on their priority and sorted by time of occurrence within each category. In this experiment alarms were be distributed based on the EEMUA 191 priority distribution. According to the EEMUA 191 standard (EEMUA, 1999), the priority distribution of alarms are 80% Low – 15% Medium – 5% High. All the alarms are predefined and there are no added nuisance alarms or distractions.

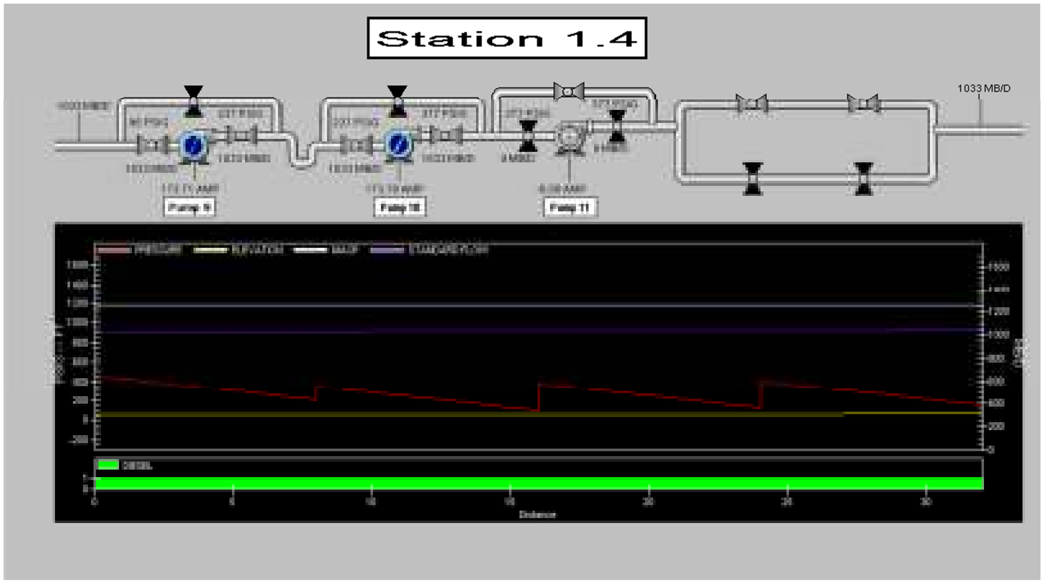


Figure 3: Detailed view of pipeline station

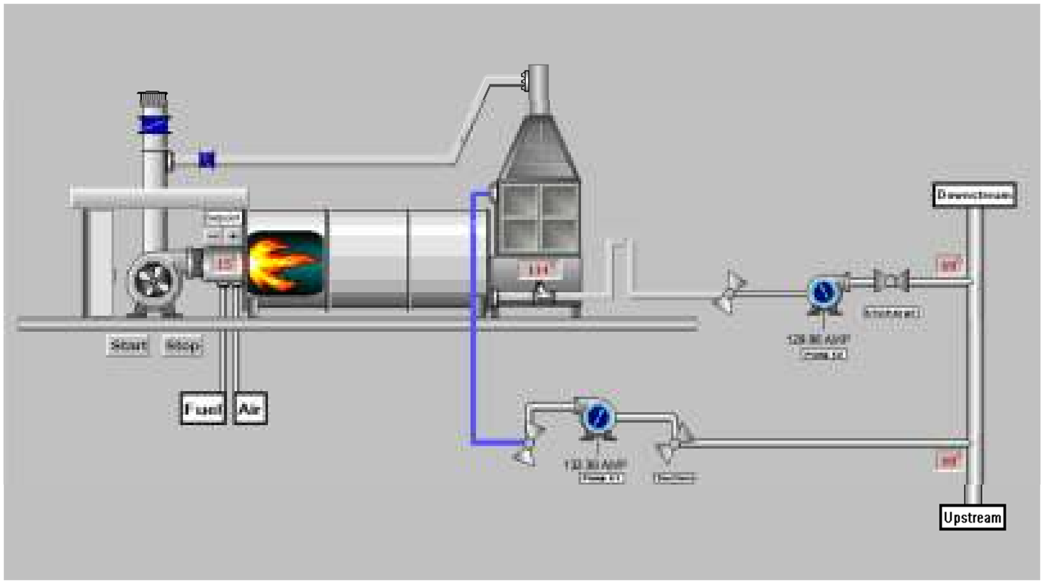


Figure 4: Dehydrator

The operator has to take action for each alarm to stabilize the flow and control the situation. In the alarm display interface, the operators are provided with alarm messages, and they need to double click the alarm message to acknowledge the alarm. The high priority alarms are displayed in red, medium priority in yellow and low priority in white. The design of the experiment was such that the workload at different intervals of time will be consistent. Alarm arrival time was randomized by type and priority. Different batches of diesel, gasoline, and crude oil were used in this experiment.

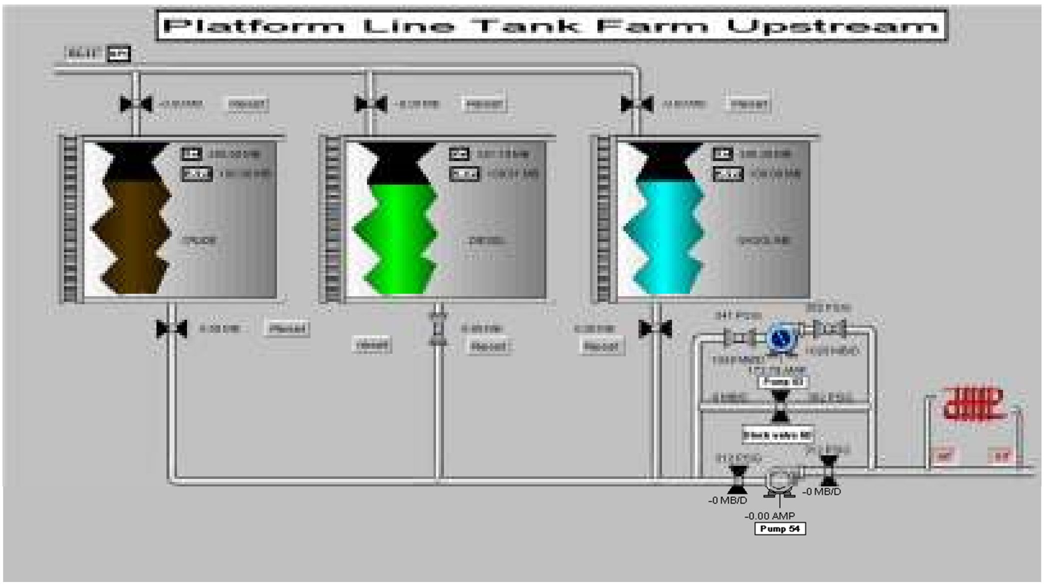


Figure 5: Upstream display of fluid

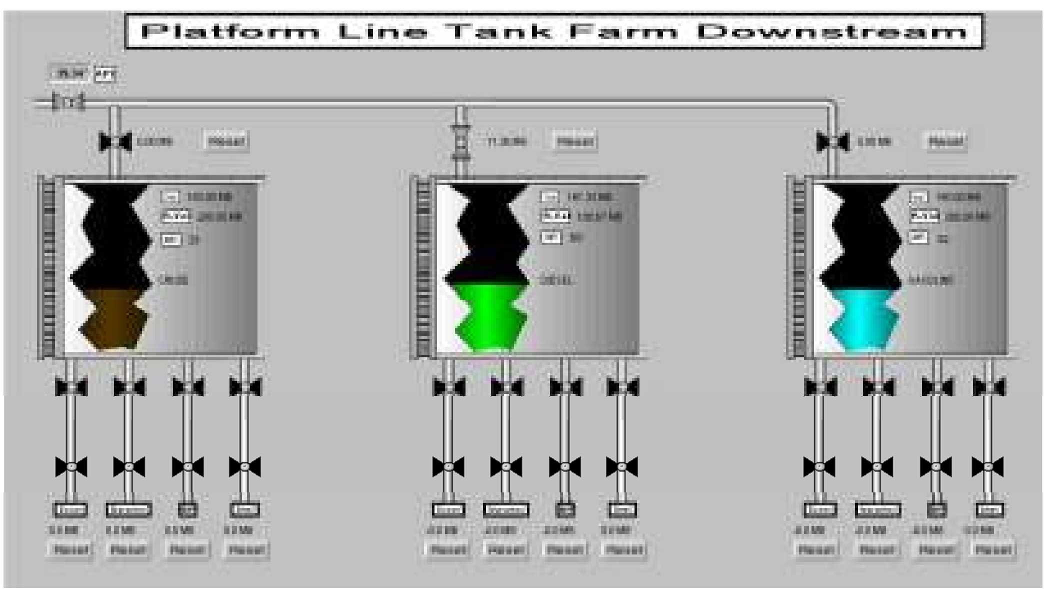


Figure 6: Downstream display of fluid

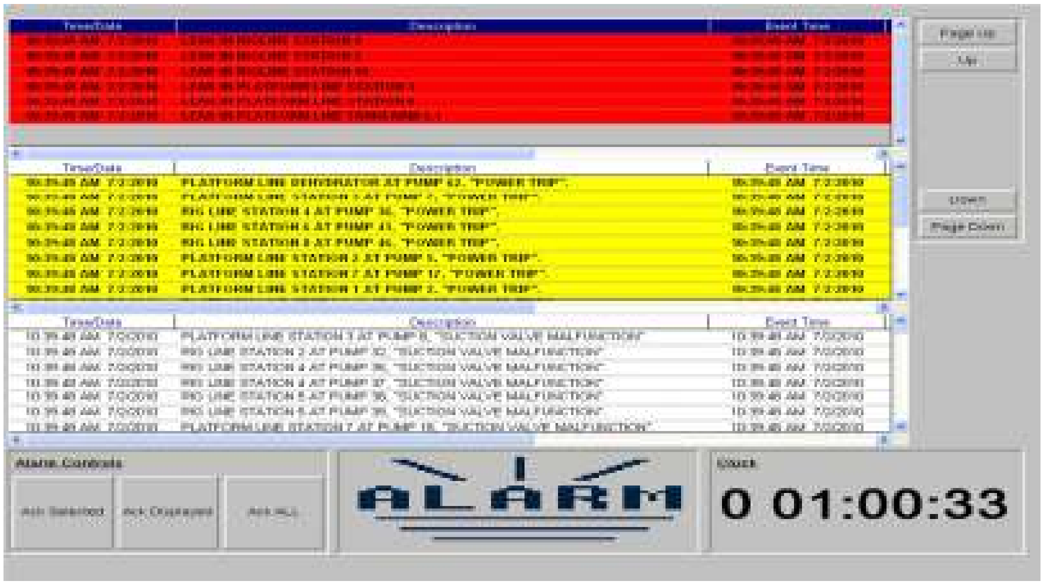


Figure 7: Categorical display

Figure 8: Chronological display

3.2 Experimental Design

The experiment was designed to collect the data and measure the performance of pipeline and refinery control room operators, who are responsible to monitor the transport of different petroleum products through the pipelines similar to what we find in this simulation. The independent variables taken for this study are:

- **Alarm Rates:**

Table 2: Alarm rates in different display types

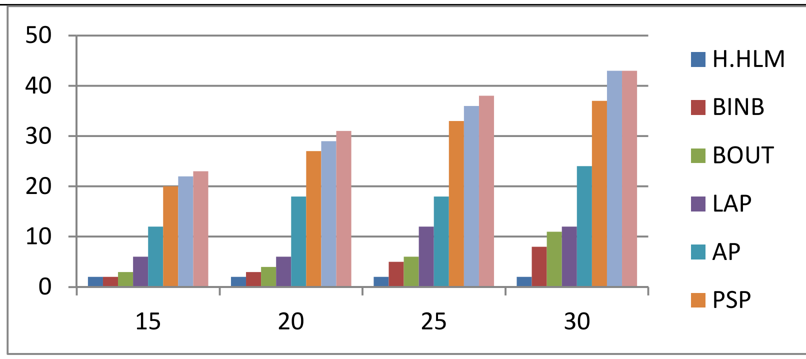
Categorical display	Chronological display
	15 per 10 minutes
20 per 10 minutes	20 per 10 minutes
25 per 10 minutes	25 per 10 minutes
30 per 10 minutes	

- **Alarm Windows –** Categorical, Chronological. In the analysis categorical display was designated as 1 and chronological display as 2.

The dependent variables are:

- **Response Time** – Time elapsed after an alarm is raised until the action procedure completed by the operator. Some alarms require multiple actions to complete.
- **Acknowledge Time** – Time operator takes to acknowledge the alarm after it gets displayed in the alarm window. The alarm message can be acknowledged by double clicking the message displayed in the alarm window and also the alarm window has three buttons (Ack-selected button, Ack-displayed button and Ack-filtered) which the operator can use to acknowledge the alarm message.
- **Accuracy of response –** This variable was used to analyze whether the operator took appropriate action to complete the task. The operator's work was observed while running the experiment and was be given score of '0' for unsuccessful completion and '1' for successful completion for each alarm.

Every effort was made to have the same work load (navigation, complexity of alarm actions, number of steps to complete the task etc.,) in all the experiments. Some of the abnormal events the operator has to handle are leak events, power failures, equipment malfunctions, and equipment failures. A list of different alarms used in the experiments are shown in (Figure 9)



List of alarms shown in the figure above
PSP – Pump suction pressure related alarms
PBP – Pump bypass pressure related alarms
PDP – Pump discharge pressure related alarms
AP – Pump power trip alarms
LAP – Leak at pump alarms
BOUT, BINB – Block valve outlet and inlet related alarms
H. HLM – Temperature rise in device alarms.

Figure 9 : Alarms distribution in different alarm rates

3.3 Experiment Approach

A total of 25 control room operators ran the experiment and each participant was trained in an effort to orient them to the type of situations they would experience during supervision and management of the simulated pipeline system. Each participant was expected to spend a maximum of 7 to 8 hours (training + six 1-hour experiments + breaks) to run all the experimental conditions and the operator's performances was measured in the form of response time, accuracy of response and acknowledge time. It took more than 250 hours to run the experiments and organize the data collected from experiments. All the participants were trained in order to familiarize them with the system. The operators were asked to complete a demographic survey in order to collect gender, age and experience details. All participants went through a training presentation (see Appendix-5), and were given demonstration of simulation. This training allowed the participants to understand the tasks they needed to complete while running the experiment. Data was collected from every participant and a decision was made during analysis whether to exclude or include participant data if there were anomalies in the analysis (homogeneity of variance was disturbed) by including the data.

3.4 Experimental Procedure

The experiments were conducted at operator control centers of well-known petro-chemical companies. Companies provided a schedule as to when the operators were available to run the experiments, and the companies were visited according to the schedule. Each operator completed 6 scenarios in the experiment. The scenario orders were randomized as shown in Appendix-1. The operator was given a 5-10 minute break between the scenarios. Training and all scenarios were completed in one day for each operator. Each operator ran (20, 25 and 30) alarms per 10 minutes scenarios in categorical and (15, 20 and 25) alarms per 10 minutes in chronological display. Operators were asked to stop the experiment after exactly 1 hour even if they had alarms still to be handled in the queue. The operator's acknowledge time and response time were automatically stored into the database. Operator operations were recorded using Morae (onscreen video capture software). The recorded video was used as a backup to manually process and extract the response and acknowledge times if there are any anomalies in the data collected through automation.

CHAPTER 4: ANALYSIS AND RESULTS

The standard analysis of variance (ANOVA) method was used to test the differences in the operator's performance for each experiment by analyzing the performance measures (e.g., acknowledge time and the response time) which were collected from the experiment. This project is an extension of the work conducted by Uhack and Harvey on the alarm rates and alarm displays (Uhack, 2010). Uhack have tested 1, 2, 5, 10, 20 alarm rates and results observed a significant difference between 10 and 20 alarm rates. In this project an alarm rate between 10 and 20 was taken and tested. Uhack results showed that categorical alarm display was better than chronological display. Here a similar approach was followed and instead of short experiments the data was collected for 1-hour to test the alarm rates 20 and 25 in both the alarm displays and analyze the data. With an increase of 5 alarms, 4 different alarm rates were designed and tested to see the threshold point where an operator's performance drops.

4.1 Model Assumptions

Twenty five operators participated in this project and during analysis 2 operator's data was excluded. Those two operator's data was excluded because they have taken a lot of time to understand the simulation and had many doubts on the working procedure of the experiments. Those two operators were assisted during the experiments and so their response times were excluded. So for this study 23 operator's data was considered. Prior to using ANOVA, the Kolmogorov-Smirnov-Lilliefors (KSL) Normality test was conducted on the reaction time dependent measure to examine the goodness of fit. Results showed that the goodness of fit null hypothesis was rejected ($p<0.05$), meaning that the data was not normally distributed. Levine's homogeneity of variance test was used to assess the homogeneity of variance. The resulting p-value of Levene's test was less than 0.05 and so it was concluded that there was significant difference of variance in the sample data. Given the failed normality test and homogeneity of variance test, SAS 9.2 PROC MIXED was used to assess the data. Proc Mixed is robust to normality and homogeneity of variance as long as the covariance matrix is acceptable (see http://www.uky.edu/ComputingCenter/SSTARS/www/documentation/mixed1.htm description). PROC Mixed was run and the covariance matrix was acceptable and thus the model was evaluated using PROC Mixed by the ANOVA and Tukey's mean test. In order to better compare the results an independent variable Display_AlarmRate combining the alarm rate and alarm display type was used in the analysis. By combining the alarm rate and alarm display into a single variable, the results can be analyzed comparing all the six experiments, instead of having the results divided on alarm display. The hypotheses tested are discussed below.

4.1.1 Hypothesis 1

Null Hypothesis 1: No differences exist in participant accuracy of response with different alarm rates.

Alternative Hypothesis 1: Differences exist in participant accuracy of response.

Dependent Variable: Accuracy of Response (see 3.2 Experimental Design).

Independent Variables: Alarm Rates.

The significance of accuracy of response between different alarm rates was tested using ANOVA using a significance level of 0.05 and to determine the difference with different alarm rates a Tukey's mean test was conducted.

Levene's test was used to assess the equality of variances in different sample data and it assumes that variances of the population (alarm rate) from which different sample data taken are equal. For this hypothesis, Levene's test (See Appendix-6:Table 3) was used to assess the homogeneity of variance of accuracy of response and the resulting p-value was greater than 0.05

and so we cannot conclude that there is a difference between the variances in the data (alarm rates). ANOVA test results showed that there was no significant effect of alarm rates on accuracy of response (see Appendix-6: Table 4)

The required actions to complete a task (respond to alarm) are predefined and the operators were also trained as what action was expected when a particular alarm condition rises. For example, if suction valve and discharge valve of a pump are opened and an alarm is displayed showing that the bypass valve is malfunctioned, the appropriate action is to close the bypass valve. In the above case if the operators accidently or intentionally opened the bypass, it is considered as a mistake and accuracy of response variable defined is set to '0' for that alarm. The hydraulics used in the simulation helps the operator to monitor the status of the pipeline and if a wrong action was taken for an alarm, they can immediately find the change in hydraulics and recheck the stations where there is a change and rectify the problem. So in this study, the first action the operator took to an alarm was considered as accuracy of response. Even though the operators were asked to stop the experiments exactly after 1 hour, they didn't feel time pressure and took their time to respond to the alarms. Every operator spent time to understand the alarm message and their response time increased with increase in alarm rate.

4.1.2 Hypothesis 2

Null Hypothesis 2: No differences exist in participant response times with alarms displayed in categorical and chronological display.

Alternative Hypothesis 2: There will be increase in participant response times with alarms displayed in chronological than categorical display.

Dependent Variable: Response Time (see 3.2 Experimental Design).

Independent Variable: Alarm display with given alarm rate.

Significance of alarm display was tested using ANOVA and to test the effect of different alarm rates in alarm displays, a Tukey's mean test was tested.

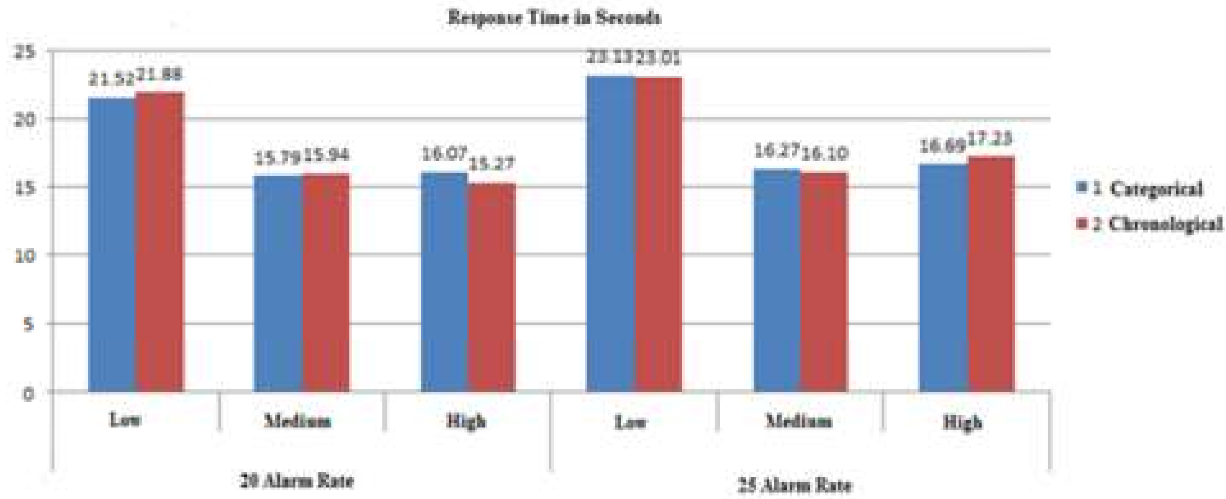


Figure 10: Response time by Alarm Display for 20 and 25 Alarm Rate

Levene's test was used to assess the homogeneity of variance and (see Appendix-7: Table 5) shows that p-value was less than 0.05 and so we can conclude that there was a difference between the variances in the population (for this hypothesis, the population is divided based on alarm rate and alarm window).

The independent variable Display_AlarmRate was used to combine the alarm rate variable and alarm display variable in order to compare all the six experiments tested on the operators. Operators did (20, 25) alarm rates per 10 minute experiments in both the categorical and chronological display and only those two alarm rates data was considered for testing the significance of alarm display. (Appendix-7: Table 6) shows that there is significant difference when the alarm rates were tested using categorical or chronological display on alarm rates. Both the alarm rates were tested to check the alarm priority significance in both the alarm displays. Average response time for each priority (Low, Medium, and High) was shown in (Figure 10). The average response times are better in categorical display, but statistical analysis didn't show any significant difference and all the priorities response times were similar.

Tukey's mean test (see Appendix-7: Table 7) shows that (30, 15) alarm rates are significantly different from other alarm rates. Alarm rates 20 and 25 did show a slight difference.

4.1.3 Hypothesis 3

Null Hypothesis 3: Operator response time will not change with different alarm rates.

Alternative Hypothesis 3: Operator response time will change with increased alarm rates.

Dependent Variable: Response Time

Independent Variable: Alarm Rate

The differences in response times with different alarm rates are tested using ANOVA and to determine the difference with different alarm rates, tukey's mean test will be conducted.

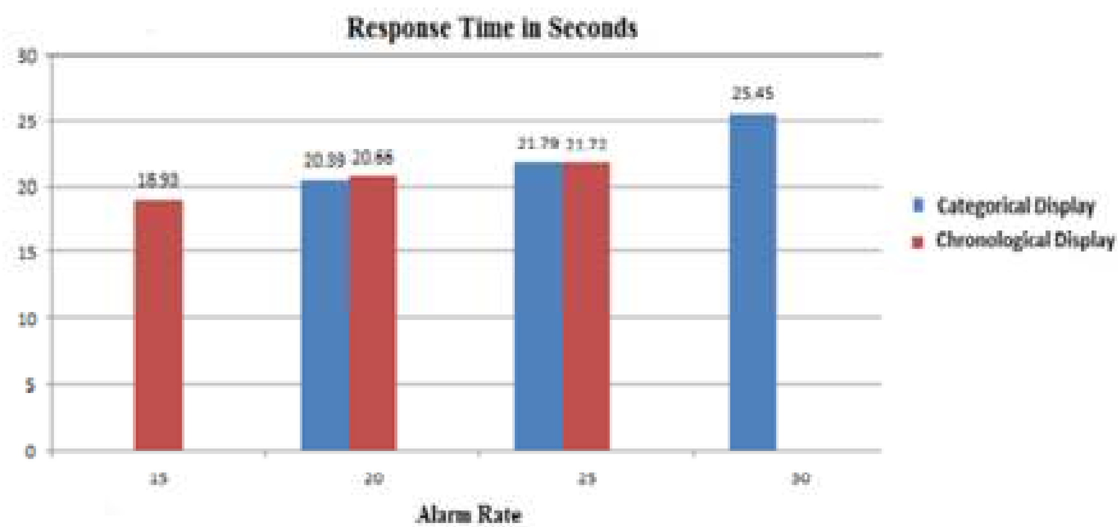


Figure 11 : Response time by alarm rate

Results show (see Figure 11) a steady increase in the response times from 15 per 10 minutes to 25 per 10 minutes and a significant difference between the 25 and 30 alarms per 10 minute response time. Both 20 alarms per 10 minutes and 25 alarms per 10 minutes alarm rates are tested using both alarm displays and there is only a slight difference in the response time between the two interfaces.

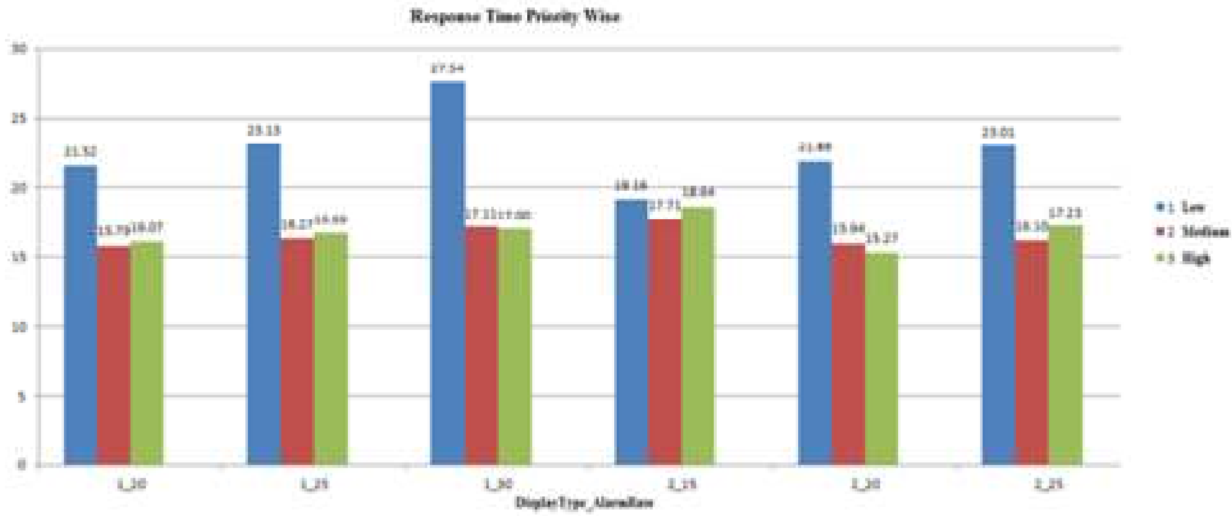


Figure 12 : Response time based on alarm type

As the alarm rate increased (see Figure 12), the operators spent less time in reacting to high priority alarms and took more time to handle low priority alarms. It shows that the operators are well aware of the alarms they need to handle first. In the process they took more time to react on low priority alarms, and chances are that they may turn into high priority alarms over the period of time in abnormal situation. Operators are trained to act on high priority alarms first and in abnormal situation with a number of alarms to respond, the operator's doesn't have control over the low priority alarms and the time operator has to make a decision is limited. Most of the low priority alarms are information alarms and it's difficult to choose the one from many to act first. Measures need to be taken to help operators respond to these low priority alarms without much trouble.

Levene's test (see Appendix-8: Table 8) shows that the resulting p-value was less than 0.05 and so it can be assumed that there is a difference between the variance in the different alarm rate responses.

ANOVA test (see Appendix-8: Table 9) was done to observe the significance of alarm rate on operator's response time and the results concluded that differences do exist in operator's response time for increased alarm rate.

A Tukey's mean test was conducted to see which alarm rates were different, and results are given in (Appendix-8: Table 10). Results clearly show that 30 per 10 minute alarm rate was significantly different than other alarm rates (alarm rates not connected by same letters are significantly different).

4.2 Observations

4.2.1 Acknowledge Time

Apart from response time and accuracy of response, acknowledge time was calculated from the operator's data. Though the acknowledge time doesn't have a direct impact on the operators performance, the results show a pattern in the operator's reaction when the alarms were displayed in different alarm displays. It was not specified during training the required routine to acknowledge the alarms, because the concentration was more on response time and accuracy of response and each operator had different approach to acknowledge the alarms. A few operators acknowledged the alarm and then took the action and a few others acknowledged the alarm after taking the action. In the second case, the recorded acknowledge time is more than the response time. Some operators have acknowledged 10, 15 alarms at once. Even when the operators were not instructed to follow a particular sequence, their acknowledge time was different when alarms were displayed using categorical and chronological displays. Acknowledge time was significantly different in both the displays and the results showed that the operators took less time to acknowledge the alarms when used categorical display. Average time to acknowledge per alarm display per alarm rate and alarm priority is given in Figure 13.

Operators tend to respond quickly when alarms were displayed in categorical display and it is clearly shown when acknowledge time for 20, 25 alarm rates was compared. Alarm displays were designed such that the alarm color is faded out when the alarms are acknowledged and the operators will not be able to identify the alarm priority once they acknowledge. Here the categorical display helps by having separate blocks for different priority and the operators can easily choose the alarms they want to work depending on their priority and this might be the reasons for better acknowledge time in categorical display. Tukey's mean test was conducted to compare the alarm rates and results are shown in (Appendix-9: Table 11).

Figure 13 : Acknowledge time

4.2.2 Response Time Considering Operators Age

Two interesting points were observed when the participant response time was calculated considering the operator's age as a factor. Operator's above 40 years were taken as one group and operators below 40 as the other group and their response times were compared. In this analysis, operators experience was not considered. There is no direct relation between age and experience. Few operators above 40 years have less experience than operators below 40 years. Out of 23 operators (see Appendix-3 for age), 12 operators were below 40 years and their average age is 32 years and remaining 11 operators aged more than 40 years and their average

age is 51 years. Every operator was given the same amount of training and they didn't start the experiments until they felt comfortable with the simulation.

It was observed while conducting the experiments that the operators above 40 years took more time to get used to the simulation. In Figure 14, effort was made to compare the results of both the age group operators and it can be observed that the response time of operators above 40 years is more than the other group. Results showed that the operators below 40 years were productive using categorical display and the operators aged above 40 years have better response time using chronological display (see Appendix-9:Table 12 and Appendix-9:Table 13 for ANOVA test and tukey's mean test results). To analyze the response times for each alarm rate for both the age groups, an independent variable DisplayRate_Age was used to combine the alarm display, alarm rate and age. Age = 1 for Operators below 40 years and age = 2 for operators above 40 years. Response time for 30 per 10 minute alarm rate is 21 sec for operators aged below 40 and is 31 sec for the other group. It means that the break point for both the age groups operators is not the same and it shows that age does play a role in response time.

4.2.3 Subject Usability Questionnaire Results

After the completion of the experiments operators were given questionnaire to know how they felt about the simulation and the experiments. All the operators liked the way alarms were displayed using different alarm windows and they were able to feel the difference in their reaction time in two alarm displays. Chart with results of all the questions answered by the operators is given in Appendix-4. Feedback was taken from each operator about their preferred alarm display window. Most of the operator's preferred using the categorical display (see Figure 15) of alarms and felt that they can be more productive by using grouping of alarms by priority.

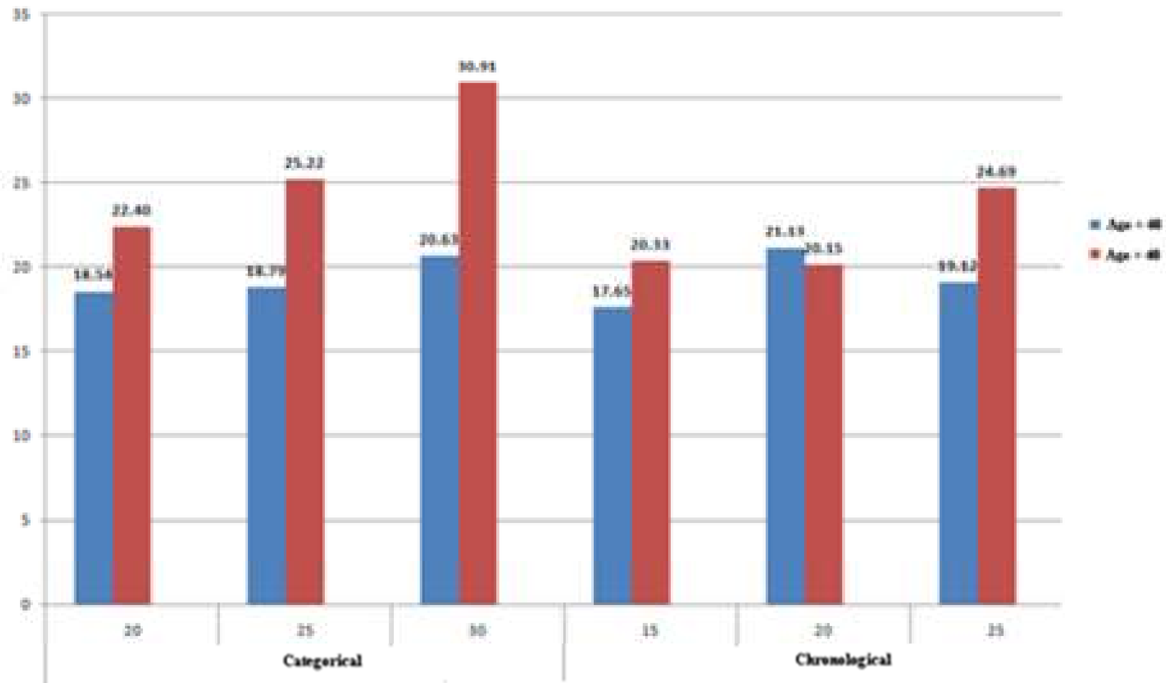


Figure 14: Response time of operators divided into two age groups

4.3 Future Research

In this project emphasis was laid on the operator's performance for given alarm rates. The tasks defined for each response were simple and so operator's accuracy of response was not tested precisely. This project must be considered from human factors point of view as the tests were designed to calculate the response time with only a handful number of tasks.

In real world, operators have to look into so many variables in order to make a decision and they communicate with ground operators to check the status of the situation.

- This project can be extended by increasing the complexity of the simulation which suits the real world operator operations.
- All the 25 operators tested were male and so future research can be done comparing the response of female operators with male operators.

- All the 25 operators did the experiments during morning shift (from 6AM to 6PM). So tests can be conducted to find the response during night shift.
- In this project, three alarm priorities were used and future experiments can be conducted by further dividing the priorities in a way to categorize the alarms based on the action the operators have to take.
- Experiments can be designed to test the fatigue and time pressure effect on the operator's accuracy of response.
- Operators can be tested by varying the shift length and analyze their response time over a period of time. Tests can be done to see the response time of operators during a shift change (example: morning shift to night shift).

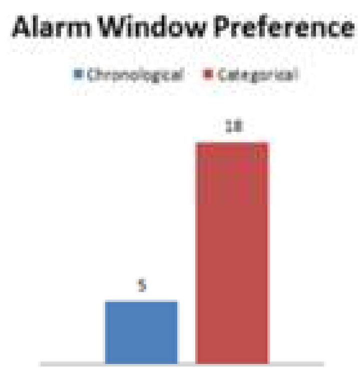


Figure 15 : Operator preference

4.4 Conclusion

Alarm management has become a major issue in modern process plants and it's been recognized as an area of weakness. The National Transportation Safety Board (NTSB) has recommended improvement in alarm management, training and human machine interface design. The design issues in alarm management include displaying the detailed information of where the problem is, and providing suggestive information to the operator in rectifying the problem. This study focused on alarm display and the interface design aspects. Results show that the performance of the operator in terms of response time is affected by an increased alarm rate and performance was dramatically different between the 25 and 30 alarms 10 minute alarm rate. Operator's response time linearly increased with change from 15 to 25 alarm rate. Between 25 and 30 alarm rates there was a difference of 4 seconds. It was observed that the operators felt it difficult to navigate to different interface screens, and at times because of the alarm flood they couldn't concentrate on the alarm message. Four seconds may not look significant, but considering the complexity of the simulation and the tasks defined, if we compare the results to the real world scenario, the operators have additional workload and need to maintain communication with ground operators. The 30 alarm rate can be considered as breakpoint (alarm rate at which the operators alarm response may be inaccurate and where the operators might feel the pressure to take decisions) from this project. In future, experiments can be designed to analyze if there is a linear increase in operator response time between 25 and 30 alarm rates to confirm the breakpoint precisely. It should be noticed that the alarm rates tested in this project are higher than EEMUA 191 standards. Even though the results did not show a significant difference in the alarm displays, operators felt more productive using the categorical display and their opinion should be considered and implemented in the pipeline industry. In an emergency situation, faced with an alarm flood, operators may have little time to respond to the situation; under higher alarm rates, operators may not take timely action or may be forced to shortcut analysis, thereby increasing the probability of a wrong decision. This project is just a beginning step to understand the importance of alarm management and operators in the petro-chemical industry.

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APPENDIX 1: TABLE SHOWING ORDER OF EXPERIMENTS

1	6	3	4	1	2	5
2	2	3	1	5	4	6
3	5	4	3	2	1	6
4	1	4	6	3	2	5
5	4	3	2	6	5	1
6	2	3	6	1	4	5
7	4	1	3	6	2	5
8	3	1	4	2	5	6
9	1	6	3	2	4	5
10	6	4	5	3	2	1
11	3	6	5	2	4	1
12	1	2	3	6	5	4
13	5	1	2	3	6	4
14	1	6	2	4	5	3
15	2	4	5	6	1	3
16	4	6	3	1	5	2
17	3	5	6	2	1	4
18	2	3	4	5	1	6
19	6	5	2	3	4	1
20	5	1	3	4	6	2
21	6	5	1	4	3	2
22	3	5	4	2	1	6
23	4	5	2	1	6	3
24	5	4	1	6	2	3
25	1	5	4	3	6	2
26	2	3	1	6	5	4
27	4	2	6	5	1	3
28	3	4	1	6	5	2
29	5	3	1	6	2	4
30	6	4	5	2	3	1

(1) - 15 in 10 minutes (Chronological)
(2) - 20 in 10 minutes (Chronological)
(3) - 25 in 10 minutes (Chronological)
(4) - 20 in 10 minutes (Category)
(5) - 25 in 10 minutes (Category)
(6) - 30 in 10 minutes (Category)

APPENDIX 2: CONSENT FORM

Title:

Determine the performance of control room operators in alarm management.

Work Site:

The experiments will be conducted at different sites to study site effects as well as different types of operator effects (e.g., pipeline vs. refinery)

Contacts:

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Purpose of the Study:

Specific objectives will be addresses in this research:

1. Evaluate different attributes and their interactions with respect to alarms on operator performance to include:

    a. Alarm rate. Alarm floods will be varied at an average specific rate (e.g., 10/minute) over a given simulation. These floods will be randomly distributed throughout the simulation so as to be more representative of the real world. All participants will receive the same random distribution of alarms.
    b. Alarm priority categories (e.g., critical, informational). Three different alarm types (e.g., high, medium, low) will be used. In this study, the data collected is used to analyze the operator performance in different categories of alarms.
    c. Alarm presentation method. Different means of presenting the alarms will be evaluated including grouping by priority, color-coding, and schematic presentation only. Methods will be drawn from literature review and industry input.
2. Develop guidelines based on the research for use by the petroleum industry in designing alarm systems including rate, priority categories, and display mode.
3. Submit additional proposed work to the Center for Operator Performance as a result of the findings from this research.
4. Performance data will be captured as a function of time (acknowledgment time, response time, accuracy of response, successful completion, alarm queue length, average time in queue). All alarms will execute within the one hour run time; however, the simulation will run until all alarms have been resolved by the controllers/operators.

5. COP will provide Subject Matter Experts (SMEs) to assist in designing the simulation conditions and for evaluating the simulation after it is built. This will ensure a higher fidelity simulation to use for real operators.
6. LSU will conduct a small (e.g., 5-10 students) pilot study of students prior taking the experiment to the field. This will be used to assess the experimental procedures.

Number of Subjects:

Thirty subjects are expected to participate in this experiment.

Study Procedures:

Experiments will be conducted using the Stoner Pipeline Simulation software available in LSU's safety laboratory. Pipeline operators will serve as human subjects with the hope to eventually recruit controllers from local petroleum companies and Center for Operator Performance's member companies after some initial work. Participants will only be included in an experiment upon successfully performing a qualifying assessment. To conduct this assessment, scaled down version of the actual experiment will be used to qualify participants to participant in the experiment. This method of qualification was used in previous research conducted in LSU's.

To evaluate the different alarm rates, data collected from the experiments is analyzed and computer interaction capture tool, Morae™, will be used if there are any anomalies in the data collected through alarm automation. Morae will allow researchers to capture operator actions for operator performance analysis and to assess operator performance in time critical scenarios based on response time, missed alarms, errors, etc. (Rothrock, Harvey, Burns, 2005).

Benefits:

Benefits which can be realized from this research are the contribution of empirical research data and performance & alarm presentation guidelines for SCADA system operators. Currently, there are many voids in the scientific community regarding controlled studies in this area.

Risks/Discomforts:

There are no known major risks involved while subjects are operating a computer. The operator needs to spend 7-8 hours of time. So they might feel tired, but that's one of the areas of interest for this research.

Right to Refuse:

It is stated that participation in the study is voluntary and that subjects may change their mind and withdraw from the study at any time without penalty or loss of any benefit to which they may otherwise be entitled.

Privacy:

This is an anonymous study.

Signatures:

'The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Robert C. Mathews, Chairman, LSU Institutional Review Board, (225)578-8692, irb@lsu.edu, and www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the researchers' obligation to provide me with a copy of this consent form if signed by me.'

Subject Signature:______________________________ Date:__________________

Illiterate subjects (When ANY subjects are likely to be illiterate, the "reader statement" and signature line below are included.)

'The study subject has indicated to me that he/she is unable to read. I certify that I have read this consent form to the subject and explained that by completing the signature line above, the subject has agreed to participate.'

Signature of Reader:_______________________________ Date:________________

APPENDIX 3: PARTICIPANTS AGE COLLECTED FROM DEMOGRAPHIC SURVEY

Participants below age 40

Participant Number	Age
1	28
2	27
5	35
6	30
7	36
11	35
12	36
14	30
19	26
20	27
21	39
22	37
Average Age	**32.16667**

Participants above age 40

Participant Number	Age
3	57
8	54
9	53
10	45
13	48
15	53
16	42
17	64
18	44
23	51
25	50
Average Age	**51**

Operators aged below 40 years

Alarm Rate	Categorical	Chronological
15		17.65245599
20	18.54412786	21.12517385
25	18.78642936	19.11735262
30	20.6324074	

Operators aged above 40 years

Alarm Rate	Categorical	Chronological
15		20.32995953
20	22.39545455	20.15075759
25	25.22363406	24.69413688
30	30.90775681	

APPENDIX 4: SUBJECT USABILITY QUESTIONNAIRE

For each of the statements below, circle the rating of your choice.

1. Overall, I am satisfied with the ease of completing tasks using this system.

STRONGLY AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **STRONGLY DISAGREE**

COMMENTS:

2. Overall, I am satisfied with the support information (messages, documentation) when completing tasks using this system.

STRONGLY AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **STRONGLY DISAGREE**

COMMENTS:

3. Overall, I am satisfied with how easy it is to use this system.

STRONGLY AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **STRONGLY DISAGREE**

COMMENTS:

4. It was simple to use this system.

STRONGLY AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **STRONGLY DISAGREE**

COMMENTS:

5. I could effectively complete the tasks and scenarios using this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

6. I was able to efficiently complete the tasks and scenarios using this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

7. I felt comfortable using this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

8. It was easy to learn how to use this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

9. I believe I could become productive quickly using this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

10. The information (on-screen messages and other documentation) provided with this system was clear.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

11. It was easy to find the information I needed to complete tasks.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

12. The information provided for the system was easy to understand.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

13. The information was effective in helping me complete the tasks and scenarios.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

14. The organization of information on the system screens was clear.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

15. I liked using the interface of this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

16. This system has all the functions and capabilities I expect it to have.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

17. Overall, I am satisfied with this system.

STRONGLY **STRONGLY**

AGREE **1☐ 2☐ 3☐ 4☐ 5☐** **DISAGREE**

COMMENTS:

18. Which alarm window did you prefer using and why?

☐**Categorical** ☐**Chronological**

COMMENTS:

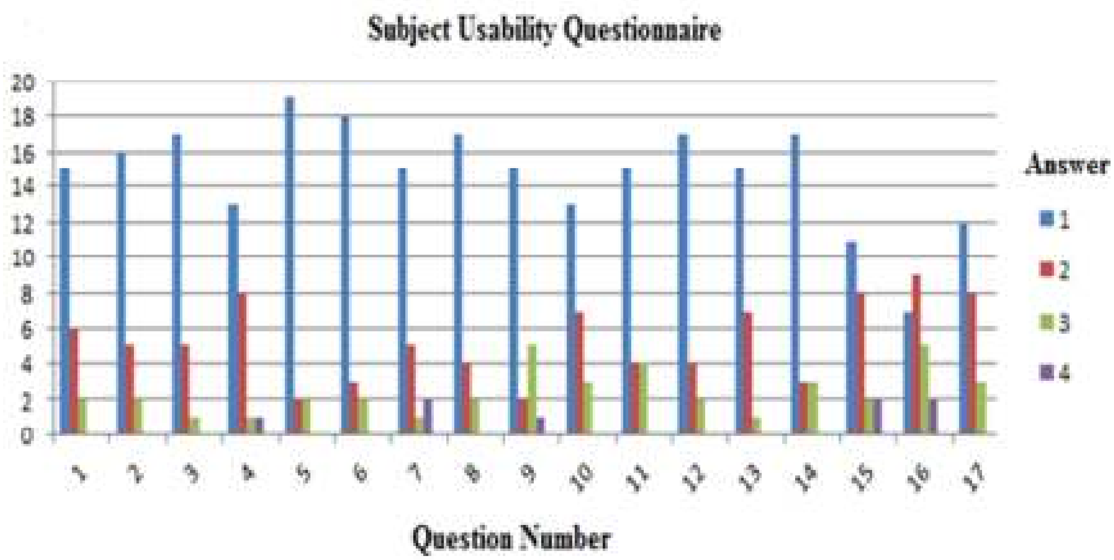


Figure 16 : Operators questionnaire results

APPENDIX 5: OPERATORS TRAINING MANUAL

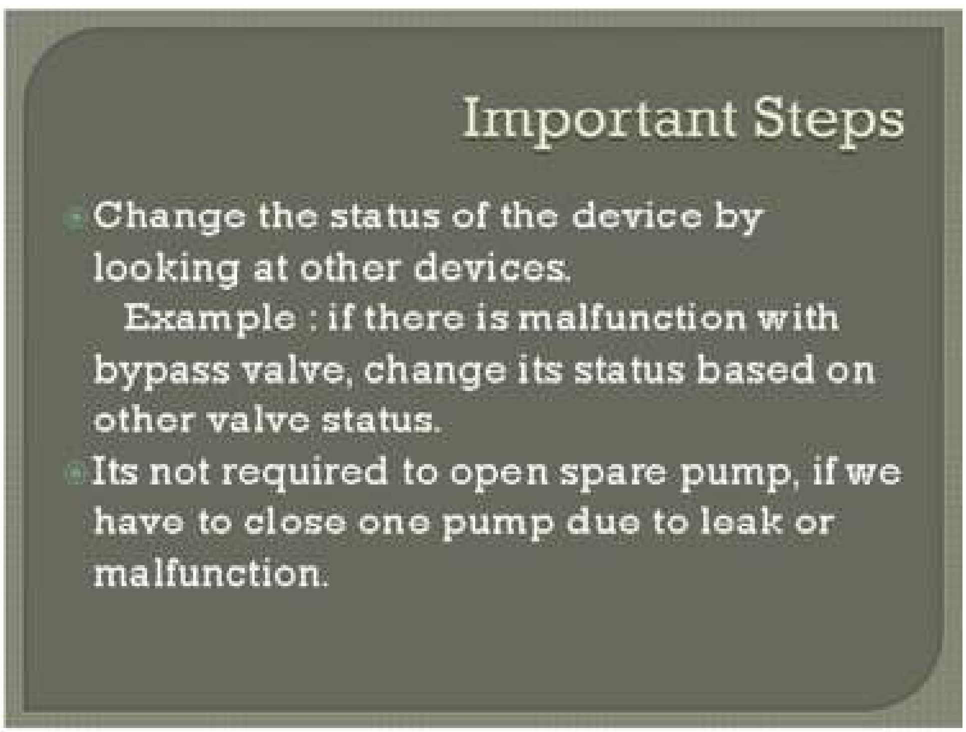
Introduction

- There are 2 pipelines (Platform and Rig).
- Each of length 72 Miles.
- Pipeline transfers Crude, Diesel and Gasoline.
- Each line have 10 stations.
- Each station have 2 - 4 pumps.
- Tank Farms at both the ends of the pipeline.
- Upstream tank farm contains a dehydrator.
- There are no slop tanks

Cont'd

- Abnormal Situation may contain
  - Leak
  - Power Trip
  - Equipment Malfunction
  - Equipment Failure
- **Leak** -- Initiate shutdown sequence for specific pump or reroute flow through Bypass Station Discharge Pipes. Do not shutdown an entire station to stop a leak at one pump.
- **Power Trip** – Restart the Equipment.
- **Equipment Malfunction** – Ensure safe operation conditions are obtained.

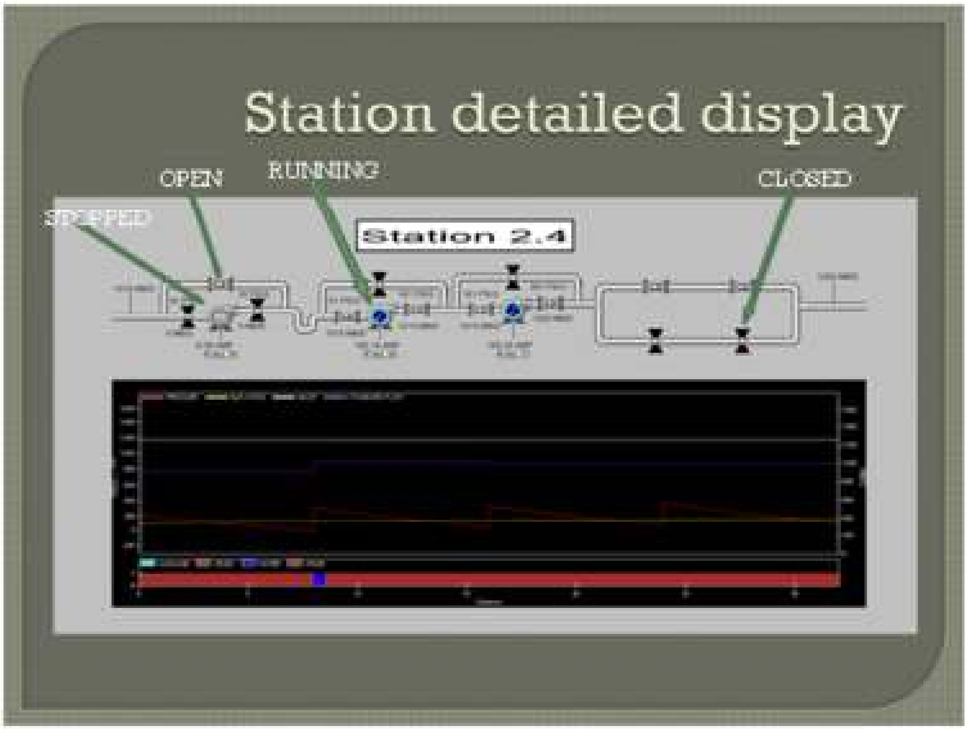

Experiments
There are 6 experiments each with a duration of 1 hour.
3 experiments will use Chronological display.
3 experiments will use Categorical display.
Alarms Priority
RED - high priority
Yellow - Medium priority
White - Low Priority

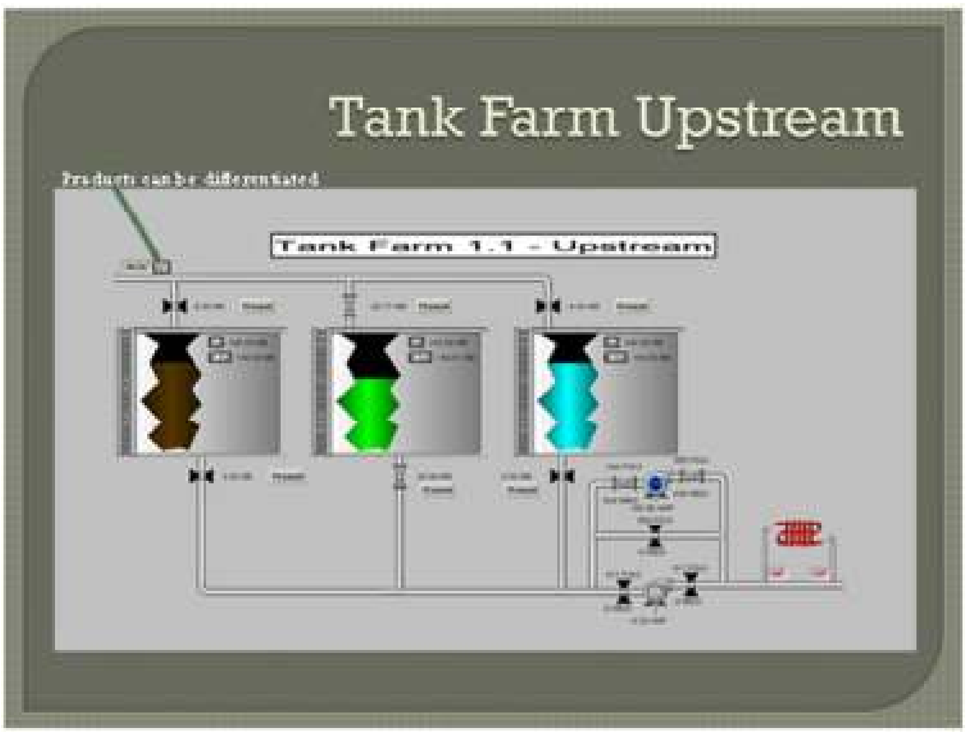

Important Steps
Change the status of the device by looking at other devices.
Example : if there is malfunction with bypass valve, change its status based on other valve status.
Its not required to open spare pump, if we have to close one pump due to leak or malfunction.

Overview of station

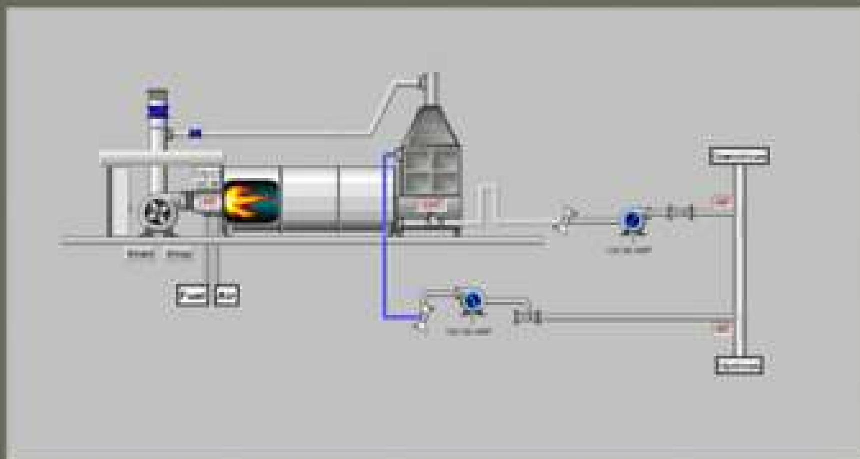
Important Steps

- In hydraulics, blue line represents flow and red line represents pressure at individual stations.
- In ideal situations blue line should be straight and above red line.
- Check the hydraulics regularly.
- In overview display the hydraulics of 10 stations are shown and in each station the hydraulics of previous, current and next station are shown.


Station detailed display
OPEN
RUNNING
CLOSED
STOPPED
Station 2.4

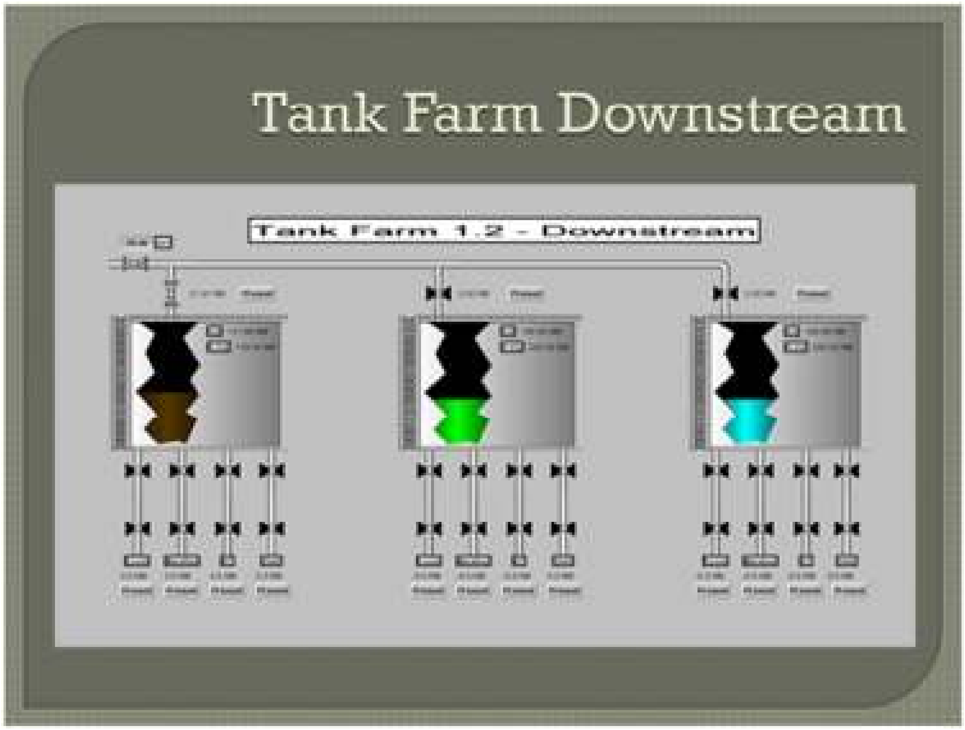

Tank Farm Upstream
Products can be differentiated
Tank Farm 1.1 - Upstream

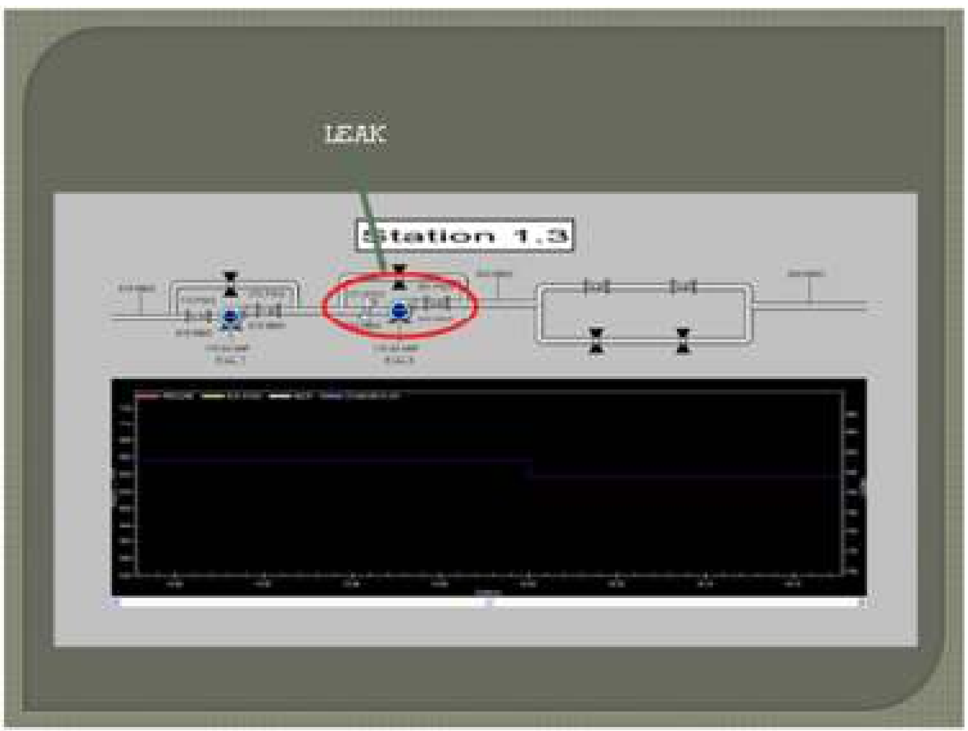
Dehydrator

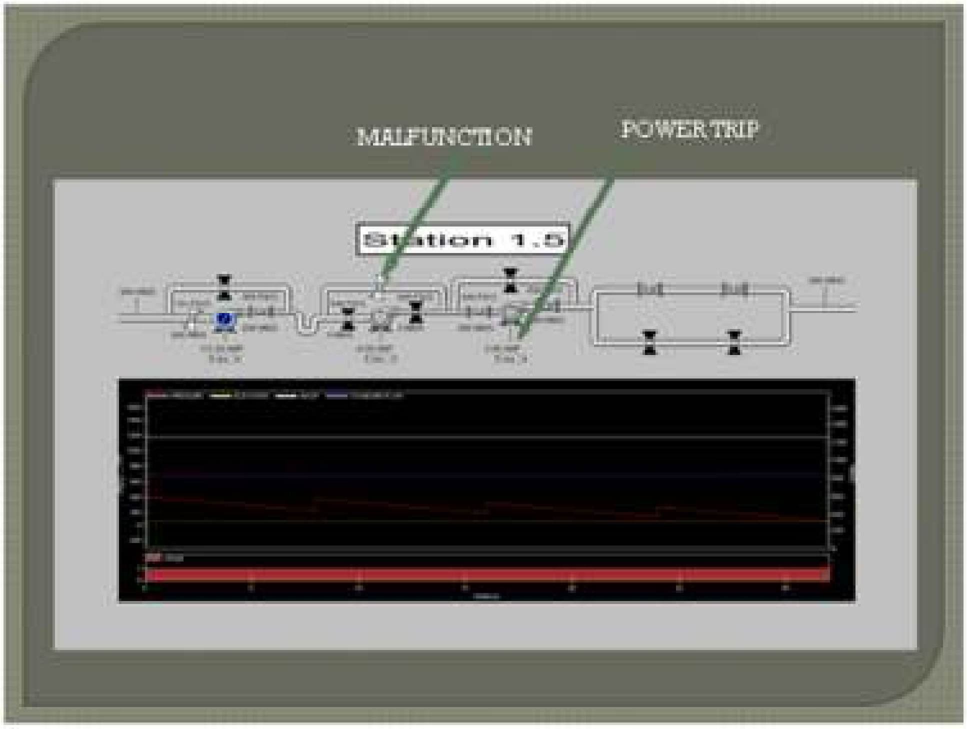


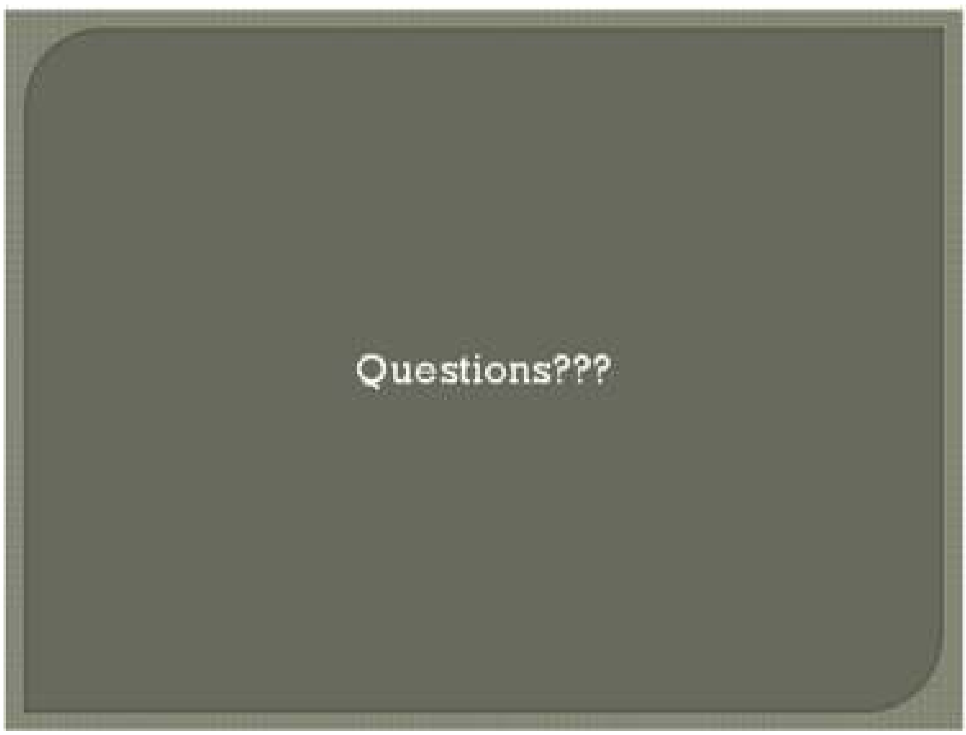
Notes

- The system can run even without dehydrator. If you find a leak in dehydrator , you have to take it out of loop by stopping the pumps and dehydrator.


Tank Farm Downstream
Tank Farm 1.2 - Downstream


LEAK
Station 1.3


MALFUNCTION
POWER TRIP
Station 1.5


Questions???

APPENDIX 6: HYPOTHESIS 1 ANALYSIS

Table 3: Levene's test to assess the accuracy of response variance

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.5276	5	18390	0.7556
Brown-Forsythe	0.5270	5	18390	0.7560
Levene	2.1114	5	18390	0.0610
Bartlett	211.4689	5	.	<.0001*

Table 4: ANOVA test to determine the significance of alarm rate on accuracy of response

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Display-Rate	5	0.004577	0.000915	0.5270	0.7560
Error	18390	31.939759	0.001737		
C. Total	18395	31.944336			

APPENDIX 7: HYPOTHESIS 2 ANALYSIS

Table 5: Levene's test to assess the alarm display variance

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	7.8470	5	18390	<.0001*
Brown-Forsythe	17.0130	5	18390	<.0001*
Levene	34.2154	5	18390	<.0001*
Bartlett	1641.9247	5	.	<.0001*

Table 6: ANOVA test to determine the significance of response time on alarm display

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Display-Rate	3	4724.8	1574.94	3.8022	0.0097*
Error	12257	5077058.7	414.22		
C. Total	12260	5081783.5			

Table 7: Tukey's mean test comparing alarm rates in different alarm display

Level			Mean
1_25	A		21.791222
2_25	A	B	21.720513
2_20	A	B	20.658811
1_20		B	20.386734

Categorical display = 1, Chronological display = 2. In the above tukey's test, convention used for different levels shown is (Alarmdisplay_Alarmrate taken as Display-Rate in Anova test). For example 1_20 means alarm rate 20 displayed in categorical alarm window.

APPENDIX 8: HYPOTHESIS 3 ANALYSIS

Table 8: Levene's test to assess alarm rate variance

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	13.0300	3	18392	<.0001*
Brown-Forsythe	28.2887	3	18392	<.0001*
Levene	56.9759	3	18392	<.0001*
Bartlett	2685.0653	3	.	<.0001*

Table 9: ANOVA test to determine the significance of alarm rate

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Display-Rate	5	80236	16047.3	18.3135	<.0001*
Error	18390	16114315	876.3		
C. Total	18395	16194551			

Table 10: Tukey's mean test on alarm rate

Level			Mean
130	A		25.451819
125	B		21.791222
225	B		21.720513
220	B	C	20.648531
120	B	C	20.386734
215		C	18.932269

APPENDIX 9: ACKNOWLEDGEMENT TIME AND AGE GROUP RESPONSE TIME ANALYSIS

Table 11: Tukey's mean test to compare different levels of acknowledge time with alarm rate

Level					Mean
2_25	A				32.315243
1_30		B			29.036136
2_20			C		26.408992
1_20			C	D	25.059804
1_25			C	D	24.653025
2_15				D	23.004838

Table 12: ANOVA test to determine the significance of age on response time

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
DisplayRate_Age	11	262645	23876.8	27.5517	<.0001*
Error	18384	15931906	866.6		
C. Total	18395	16194551			

Table 13: Tukey's mean test on response time based on age group and alarm rate

Level					Mean
1_30_2	A				30.907757
1_25_2		B			25.223634
2_25_2		B			24.694180
1_20_2		B	C		22.395455
2_20_1			C	D	21.125174
1_30_1			C	D	20.632407
2_15_2			C	D	20.329960
2_20_2			C	D	20.150758
2_25_1			C	D	19.117353
1_25_1				D	18.786429
1_20_1				D	18.544128
2_15_1				D	17.652456

Categorical display = 1, Chronological display = 2. Age = 1 for operators age below 40 years and age = 2 for operators above 40 years of age. In the above tukey's test, convention used for different levels shown is (Alarmdisplay_Alarmrate_Age). For example 1_30_2 means alarm rate 30 displayed in categorical alarm window tested for age group above 40 years of age.

VITA

Dileep Buddaraju was born in Varni, Andhra Pradesh (India), in 1987. He received a bachelor's degree in computer science and information technology at the Jawaharlal Technological University, Hyderabad in May 2008. He started his work towards the degree of master's in engineering science after graduating with his bachelor's degree in 2009. He worked as a research assistant during his time as a master's student in the Department of Industrial Engineering.