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## Effect of different alarm interfaces on controller response

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# EFFECT OF DIFFERENT ALARM INTERFACES ON CONTROLLER RESPONSE

A Thesis

Submitted to the Graduate Faculty of the  
Louisiana State University and  
Agricultural and Mechanical College  
in partial fulfillment of the  
requirements for the degree of  
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in

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by

Aritra Datta

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## **ABSTRACT**

Pipelines transport millions of barrels of petroleum products every day. Oil and gas pipelines have become important assets of the economic development of almost any country. Government regulations or internal policies regulate the safety of the assets for the population and environment where these pipelines run.

Various strategies and technologies have been introduced for monitoring pipelines, but the most common technology to protect pipelines from occasional hazardous incidents is Computational Pipeline Monitoring (CPM). This technique collects and gathers information from the field related to pressures, flows, and temperatures to estimate the hydraulic behavior of the product being transported. Using the gathered information CPM systems compare its values with standard values and provides a notification if any anomaly or unexpected situation occurs. The result is an alarm to an operator in a supervisory control room. According to Hollifield, it is becoming an increasing problem that there is no standard for plant operators yet, whereas improved design can lead to better performance (Hollifield et. al., 2007). So, the objective of this experiment was to explore the effect of different alarm interfaces on controller response at different alarm rates.

A simulated liquid pipeline system was developed and a between subject experimental design was performed to evaluate three different types of alarm window interfaces (Categorical, Chronological, and Revised Categorical), two alarm rates (10 in 10 minutes and 20 in 10 minutes), and three levels of alarms (high, medium, and low). Thirty one participants participated in this research, and the performance of participants was measured in terms of acknowledgement time, response time and the accuracy of response. Results showed that the participants' performance in terms of response time, acknowledgement time, and accuracy of

response was significantly different between chronological, categorical, and revised categorical displays. Data analysis showed that the means were shorter in revised categorical display in terms of response time, acknowledgement time, and accuracy of response. This study will be useful in developing new standards for alarm display.

## **CHAPTER 1: INTRODUCTION**

Pipeline transport is the transportation of goods through a pipe. Most commonly, liquids and gases are sent, but any chemically stable substance can be sent through a pipeline. Therefore sewage, slurry, water, or even beer pipelines exist, but arguably the most valuable are crude petroleum and refined petroleum product including fuels like oil, natural gas, and biofuels.

Dmitri Mendeleev first suggested using a pipe for transporting petroleum in 1863. (Tverdohleb, 2012) Since then pipelines have been used as the primary transportation for petroleum and liquidated petroleum products. Pipelines can be the target of vandalism, sabotage, or even terrorist attacks, but predominantly can face serious accidents due to device failure or malfunction. So, to reduce the risk of accidents and for gas pipeline safety, many measures have been taken, and the most popular one is using human operators to supervise and control the pipeline system. Supervisory Control and Data Acquisition (SCADA) systems are used to collect data from pipeline sensors where human controllers monitor the data from a remote site, and an alarm management system is used to notify operators of conditions outside normal operating conditions as established through engineering design.

Though many cautionary measurements have been taken by petroleum industry, it has lost billions of dollars in major pipeline accidents because of delays in finding problems and taking appropriate corrective actions (NTSB, 2005). For instance, in November 1, 2007; a propane pipeline exploded near Carmichael, Mississippi, about 30 miles (48 km) south of Meridian, Mississippi. Two people were killed instantly and an additional four were injured. Several homes were destroyed and sixty families were displaced. The pipeline was owned by Enterprise Products Partners LP, and runs from Mont Belvieu, Texas, to Apex, North Carolina. Inability to find flaws in welded pipe seams was a contributing factor to the accident.

A study conducted in petrochemical and refining operations by Butikofer (2007) observed that the cause of accidents could be attributed to operator and maintenance errors (41%), equipment and design failures (41%), inadequate procedures (11%), inadequate or improper inspection (5%) and other (2%) (Formosa Plastics Corp., 2007). Human errors can occur because of many reasons including poor interface design and alarm management system, lack of proper operator training, fatigue etc. Though research continues to identify better methods, there is ample opportunity for improvement on supervisory and control systems for these complex systems.

## **CHAPTER 2: LITERATURE REVIEW**

### **2.1 SCADA**

Supervisory Control and Data Acquisition (SCADA) is a computer system for gathering and analyzing real time data. SCADA systems are used to monitor and control a plant or equipment in industries such as telecommunications, water and waste control, energy, oil and gas refining and transportation.

From a central reading location, a SCADA system can track a number of remote sites equipped with Remote Terminal Units (RTUs) or Programmable Logic Controllers (PLCs). The RTU/PLCs can measure an array of conditions and a wider variety of parameters, including temperature, current, voltage flow, and tank levels.

The data acquired is then sent back via a communication link. Some of the larger systems can monitor 10-20,000 remote sites, with each site handling as many as 2000 input/output (I/O) points. These units in turn report back to the Central Processing Unit (CPU) that carries out the control functions and needed analysis.

Figure 1 is a representation of a SCADA system in oil and gas industry. Crude oil is gathered from different wells, and then it is transported to refineries through a pipeline system. Refined oil products are transported from refineries to a tank farm and finally transported to a pipeline company and different distribution companies through the pipeline system. All of the transportation through pipelines are controlled by the SCADA system. The SCADA system has an important contribution to oil and gas industry as well as other continuous process industries.

#### **2.1.1 SCADA System Use**

In the oil and gas industry, refineries are forced to control their operations to reduce environmental impact as well as prevent accidents. Emissions of Volatile Organic Compounds

(VOCs) associated with applicable process vents, equipment containing or contacting hazardous wastes, and tanks and other units used for storage of hazardous wastes. VOCs are responsible for causing ground-level ozone and are also toxic.

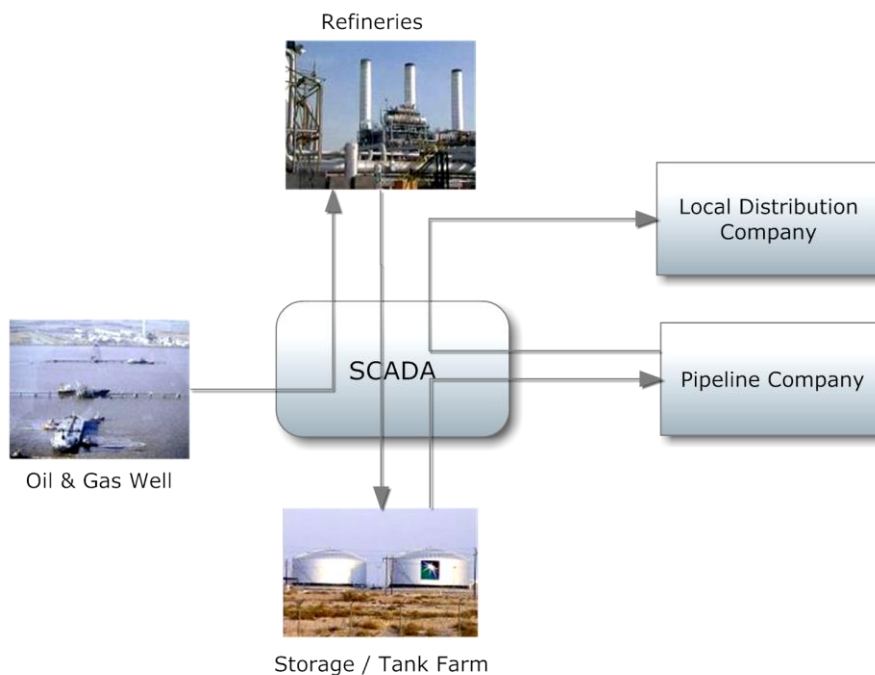


Figure 1: Overview of the Transportation System of Oil and Gas Industry

Most oil refineries are located near East and West Coast population centers (U.S. House of Representatives, 1999). From an American Petroleum Institute (API) report, it can be found that during the period of 1976 to 1980 fire-related losses were averaging \$114 million per year, with a high value of \$316 million in 1980. These losses, an average of \$69 million, or 60%, occurred in oil refineries (Pate-Cornell, 1985). Fire is considered as the most frequent type of loss with 145 cases and explosion is considered as the second most frequent type of loss with 61 cases. Fire and explosion together accounted for 85% of the total cases. Oil spill and toxic gas/liquid release were the third and the fourth most frequent, respectively. Considering the month in January 2002, the average property loss of the 10 largest storage tank damage losses

was 114 million dollars. From incidental facts it can be assumed that accidents occurred more frequently at petroleum refineries (Chang and Lin, 2006). Maintenance error was the second most frequent cause for oil and gas storage tank accidents, and other causes include equipment failure (*e.g.* valve failure, heater malfunctions, thermostat failure, analyzer failure), leak, open flames, static electricity etc. (Chang and Lin, 2006). So, from the above facts it can well be assumed that refineries can be hazardous to human life (and plant as well). So, safety of oil and gas plants should be the first concern among all priorities. Managing these complex systems is accomplished by SCADA systems which are used to monitor and regulate liquid flow, reservoir levels, pipe pressure and ultimately help to run a gas plant securely.

Distributed Control Systems (DSC) is used by operators operating machines or plants near them, whereas centralized systems can be used by fewer operators operating plants in a remote DCS room, and that is why these days in many cases supervisory control systems have been changed from distributed to centralized systems. Because of this change, systems now have to process or display much more information, and so their human interfaces must be changed, too. (Hori and Shimizu, 1999)

## **2.2 Laws, Regulations and Standard in the Petrochemical Industry**

There are many laws, regulations and standards to be maintained in petrochemical industry and refinery.

### **2.2.1 Laws and Regulations**

There always has been a demand for oil and natural gas all around the world and in supplying the world's energy needs, pipeline companies face unprecedented environmental and regulatory challenges. As the country expands its energy infrastructure, the safe and reliable delivery of oil and gas via the nation's pipelines has come under intense scrutiny. To maintain



the safety and reliability many new laws and regulations, described below, have been created most recently. Several of these new rules and regulations will be discussed below.

#### PIPES Act

The Pipeline Inspection Protection Enforcement and Safety (PIPES) act was introduced in 2006. It was created to provide enhanced safety and environmental protection in pipeline transportation, and enhanced reliability in the transportation of the United States' energy products by pipeline. (PIPES Act, 2006)

#### PHMSA

Pipeline and Hazardous Materials Safety Administration (PHMSA) 192.631(d) and 195.446(d) regulations are introduced as a result of the PIPE Act. These regulations require pipeline operators to consider human factors in the design of their SCADA systems and work rules. For example, companies are required to follow API 1165 which promotes human factors in the design of display systems. Likewise the regulations outline rules to reduce the risk associated with controller fatigue that could inhibit a controller's ability to carry out the roles and responsibilities that the operator has been defined. These regulations also help to establish shift lengths and put a maximum limit on controller hours-of-service, which may provide for an emergency deviation from the maximum limit if necessary for the safe operation of a pipeline facility. It also discusses scheduling rotations, and educating controllers and supervisors on fatigue mitigation strategies and how off-duty activities contribute to fatigue. It further discusses that companies must train controllers and supervisors to recognize the effects of fatigue.

#### **2.2.2 Standards**

Different standards have been developed to help companies manage SCADA systems. Table 1 represents many of the important standards as related to this thesis.

Table 1: Different Standards for Oil and Gas Industry

Standard	Publishing Organization	Date	Description
EEMUA 191	The Engineering Equipment and Materials Users Association	1999 2 <sup>nd</sup> edition in 2007	Its main mission is to improve quality and safety of monitor system performance and to reduce the cost of operating industrial facilities. Finding solutions on alarm management <i>i.e.</i> find a better approach for alarm management. Distinctive differences are found between ineffective alarm system and effective alarm system in 2 <sup>nd</sup> edition of EEMUA 191.
API 1165	API Recommended Practice	2007	Its primary purpose is to document industry practices and provide guidance to a pipeline company or operators, who want to select a new SCADA system, or update or expand an existing SCADA system. This recommended practice focuses on the design and implementation of displays used for the displays, monitoring, and control of information on pipeline Supervisory Control and Data Acquisition Systems (SCADA).
API 1167	API Recommended Practice	2010	It provides guidance on elements that include, but are not limited to, alarm definition, alarm philosophy, documentation, management of change, and auditing.
API 1168	API Recommended Practice	2008	The purpose of this publication is to provide pipeline operators and pipeline controllers with guidance on industry best practices on control room management to consider when developing or enhancing practices and procedures.
ISO 11064	International Organization for Standards		It establishes ergonomic principles for the layout of control rooms. It includes requirements, recommendations and guidelines on control room layouts, workstation arrangements, the use of off-workstation visual displays and control room maintenance.
ISA 18.2	International Society of Automation	2009	This standard addresses the development, design, installation, and management of alarm systems in industries. Alarm system management includes multiple work processes throughout the alarm system lifecycle. This standard defines the terminology and models to develop an alarm system, and it defines the work processes recommended to effectively maintain the alarm system throughout the lifecycle.

### **2.2.3 Organizations**

In addition to guidelines for the petrochemical industry, several organizations play a role in helping to maintain a safe industry.

#### **Abnormal Situation Management (ASM)**

ASM Consortium is a research and development consortium founded in 1994 by Honeywell. It aims to identify problems regarding industrial plant operation during abnormal conditions, and to develop solutions. Abnormal situation management, like general emergency management, is achieved through prevention, early detection, and mitigation of abnormal situations, thereby reducing unplanned outages, process variability, fires, explosions and emissions that are reducing profits and putting life at risk. ASM Consortium has produced documents on best practices in alarm management, as well as operator situation awareness, operator effectiveness, and other operator-oriented issues.

#### **International Society of Automation (ISA)**

ISA is one of the foremost professional organizations in the world for setting standards and educating industry professionals in automation. It was officially established on April 28, 1945 as the Instrument Society of America. It has 17 different technical divisions; some of them are Computer Technology, Process Measurement and Control, Safety, Chemical and Petroleum Industries. Modern industry is a complex interaction of numerous systems, and all these divisions provide standards for different measurement and control devices, which permit greater flexibility in the operation of these complex systems.

#### **American Petroleum Institute**

API founded in 1919 as non-profit National Trade Association, and the API Standardization Department was formed in 1924. API is accredited by the American National

Standards Institute (ANSI). This organization tries to influence public policy in support of strong US oil and natural gas industry, and engaged in legislative and regulatory advocacy. It develops industry standards that ensure reliability and codify best work practices.

### **2.3 Operator Performance**

Human factors engineering concerns the design of equipment in accordance with the mental and physical characteristics of operators. Human operators play a big role in water, power and electric, and oil and gas industry. According to Ian Nimmo (2008), studies conducted by the Abnormal Situation Management Consortium, American Institute of Chemical Engineers, American Petroleum Institute, American Chemistry Council, and similar organizations have all concluded that about 80% of the root causes contributing to major accidents affecting safety, environment, and/or economics are linked to human operator error. Human errors are caused by many variables including errors due to a task that is beyond the physical or mental ability of the person asked to do it, a slip or momentary lapse of attention, errors due to a deliberate decision not to follow instructions or accepted practice, poor training or instructions, or poor human machine interface design. Uhack (2010) said there has been research to find best practices for pipeline control room operators; however no specific empirical literature was found that considered alarm rates and interface design for pipeline control room operators. The Engineering Equipment Materials and Users Association (EEMUA) No. 191 authors imply that research conducted in the process industry or elsewhere in a control room setting, e.g. a refinery or similar control room environments, can be used to improve human factors design and benchmark performance in the pipeline industry, as well as other industries. SCADA system impact on operator performance and the performance solely depends on the design of a SCADA system. So, to design a better SCADA system it is highly recommended to understand the elements,

which control the operator performance. Therefore the elements that can affect operator performance are discussed below.

### 2.3.1 Operator workload

Operator workload and performance, as displayed in Figure 2, have an inverted U relation. At extremely low level of workload, region 1, the operator might become bored (Hart, 1986a).

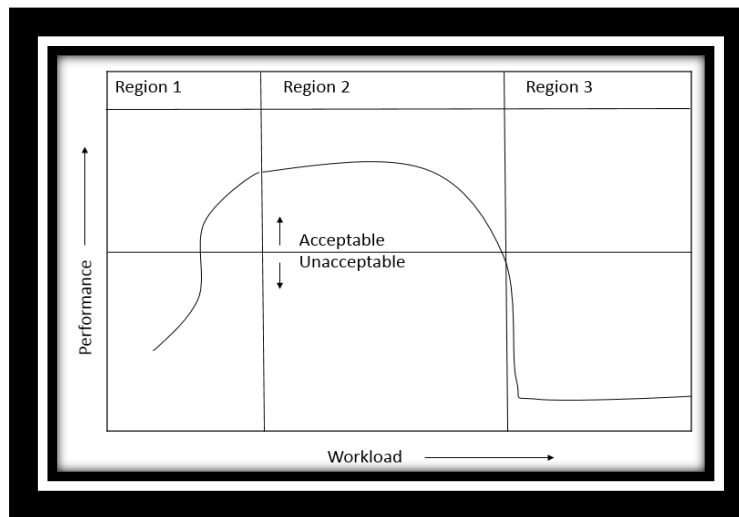


Figure 2: The hypothetical relationship between workload and performance. (Hart, 1986a; O'Donnell and Eggemeier, 1986; Tole, Stepherns, Harris, 1982)

Boredom can lead to missed signals or instructions resulting poor performance (Parasuraman, 1986). Reasonable level of workload, region 2, generates acceptable performance. Whereas, a further increase of workload can lead to a degradation in performance, region 3. So, without an optimum amount of workload disaster could occur. Workload with SCADA system is an important element that can affect optimum performance.

An operator's performance depends upon not only workload but also various factors, shown in Figure 3 (Lysaght *et al.*, 1989).

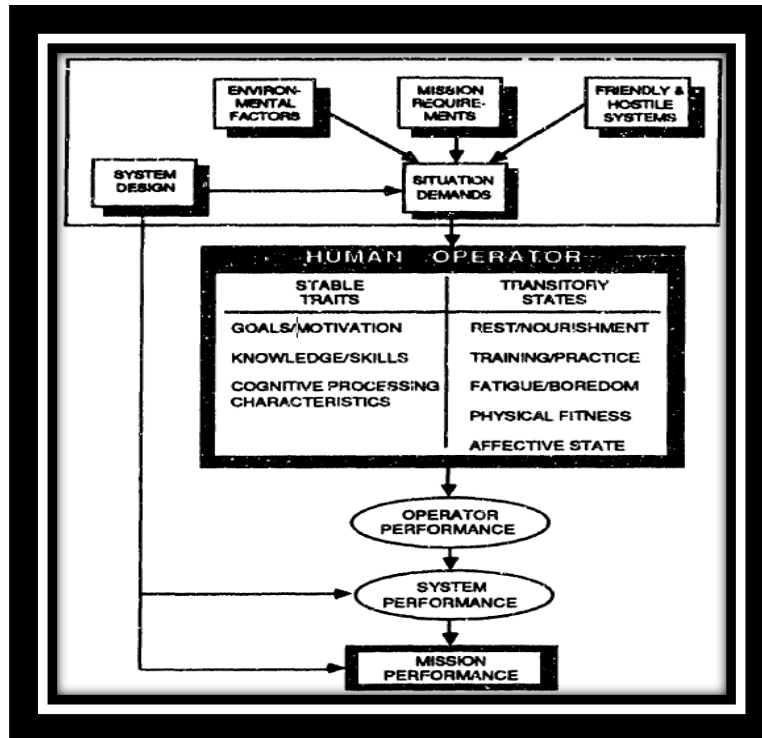


Figure 3: A conceptual framework of the operator workload (OWL) context and influences on operator/system performance (Lysaght et. al., 1989)

Tasks can influence the workload that will be imposed on the operator by:

- Actions required by each task.
- Sequence of actions performed for a task.
- Number and types of tasks to be completed.
- Overall time constraints, and
- Required accuracy levels.

So, together these influences constitute a comprehensive set of factors that contribute to the situation demands illustrated in Figure 3.

Apart from above mentioned factors, there are more crucial factors which affect operators' performance, and among those important one is fatigue.

### 2.3.2 Fatigue

The recent rapid proliferation of information technologies has resulted in expanded operations with VDTs (visual display terminals) and increasing numbers of operators that report physical and mental fatigue (Hachiya *et al.*, 2010). VDT operations involve prolonged sitting in front of displays, which results in restricted movement, and therefore fatigue is more likely to build up than in general office work by that unavoidable restricted posture. The general notion of fatigue is defined rather vaguely, including that associated with VDT operation. It is very difficult to find exact reasons for fatigue and there is no established method of monitoring the fatigue of VDT operators. There are many factors that can cause fatigue including sleep deprivation, repetitive work, and high stress.

In 1979, the meltdown at the Three Mile Island nuclear plant in Pennsylvania occurred at 4am by operators working the night shift. Experts believe fatigue may have been a contributing factor. The Chernobyl nuclear power plant incident in the Ukraine on April 26, 1986 started at 1:26am, and the cause of the disaster has been partially attributed to fatigue. (Occupational Health Management, 2008)

In oil and gas refineries operators control tank levels, flow in pipelines, pipeline temperature by maneuvering a SCADA system, which is a strenuous job as they have to sit in front of displays and control the system for hours. The long shift (specially the night shift) causes fatigue that is also often mentioned as a possible factor in the occurrence of accidents as it may decrease the ability to process information about a hazardous situation and also it may decrease the ability to adequately respond to a hazardous situation (Swaen, 2002). So, fatigue might be considered as one of the key reasons for all accidents in the petroleum and allied industries. Because of accidents companies end up facing huge monetary loss in liabilities.

### 2.3.3 Operator Error and Training

It is said that the operator or human error is an inappropriate or undesirable human decision or behavior that reduces, or has the potential for reducing, effectiveness, safety, or system performance (Sanders *et. al.*, 1993). Various error classification schemes have been developed over the years to classify human errors in an attempt to provide useful insights on their cause, so that, they can be prevented.

One of the simplest error classification schemes is the Swain and Guttman (1983) discrete-action classification, which includes:

- Errors of omission (failure to do something)
- Errors of commission (performing an act incorrectly)
- Sequence errors (subclass of errors of commission, involves error in multi-step task)
- Timing errors (subclass of errors of commission, involves failure to perform within allotted time)

Swain and Guttman explained that a very common human error is forgetfulness; human tend to forget to do required work. The major impact occurs when human performs any task incorrectly, which has huge impact and might lead to a disastrous incident. Time management is another important factor, usually multilevel task takes more time, which might lead to a critical situation.

Rasmussen (1982) identifies 13 types of errors to establish his approach. Rasmussen (1982) makes a provocative point that an action might become an error only because the action is performed in an unkind environment that does not permit detection and reversal of the behavior before an unacceptable consequence occurs. Although many people tried to find error



classification schemes, no scheme has really been particularly useful; because human error is complex which leaves ample area still to work on and find a better solution. It is inevitable that humans will err. There are numerous strategies for reducing the negative impact or consequences of human error, but most important ones are proper selection, training, and design.

#### 2.3.3.1 Selection and Training

Selecting people with the capabilities and skills required to perform a job will result in fewer errors being made. Such things as perceptual, intellectual, and motor skills should be considered. The limitation with this approach are that (i) it is not always easy to determine what skills and abilities are required, (ii) reliable and valid tests do not always exist for measuring the required skills and abilities, and (iii) there may not be an adequate supply of qualified people. Errors can be reduced by proper training of personnel. Unfortunately, people do not always perform as they were trained. They can forget or revert to old habits acquired before training. Training can also be expensive because it must be given to each person and, in critical situations, should include refresher training as well (Sanders et. al., 1993).

Crichton (Crichton, 2001) mentioned that training is required to improve individual skill on decision making, communications, shared situation awareness, co-ordination. He said that “training results in more effective and efficient decision making, accelerated proficiency and the development of expertise in individuals and teams, issues that are particularly crucial in complex, critical and hazardous real-life situations, such as emergencies”.

### 2.4 Interface Design

Workplace design or equipment designing is one of the most important factors that can help reduce human or operator error and improve the performance. There are three generic design approaches for dealing with human error:

Exclusion designs: The design makes it impossible to commit the error.

Prevention designs: The design of things makes it difficult, but not impossible, to commit the error.

Fail-safe designs: The design of things reduces the consequences of errors without necessarily reducing the likelihood of errors. (Interaction Design, Wiley, 2007)

In the petroleum industry operators' work structure involves receiving feedback from the SCADA system that requires them to analyze and integrate multiple forms of information, and then take the necessary steps to maintain the best possible condition. Figure 4 gives an insight of operators' workplace. It is noticeable in the picture that an operator's room consists of many displays, and an operator has to control an entire pipeline system by observing and understanding this intricate design. It is understandable that a badly designed SCADA system might lead an operator to take a wrong move resulting disaster.

The interface design is critical for notifications or warnings. Purposes of warnings are to (i) inform the users or operators of a hazard or danger, of which they might not be aware, (ii) remind operators of a danger at the time and place where the danger is most likely to be encountered. According to Nimmo companies don't really understand the importance of alarm management until a disaster happens (Nimmo, 2011). A better designed alarm display might help to prevent many disastrous situations.

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



Figure 4: Operators' Workplace

Poorly functioning alarm systems have contributed to hazardous incidents and major accidents. Significant alarm system improvement is needed in most industries that utilize computer based distributed control systems; it is a massively common and serious problem. Most companies have become aware that they need to thoroughly investigate and understand their alarm system performance. Alarm management is a fast growing, high profile topic in the process industries. It is the subject of constant articles in the trade journals and at various technical society meeting and symposia (Hollifield and Habibi, 2010).

The efficiency of alarm management depends on several guidelines on design, implementation, reengineering, and these guidelines help operators to take correct action at the correct time in response to an abnormal situation, but if alarms population and operators maintain following guidelines (Hollifield, 2006).

- Alarms are properly chosen and implemented.
- Alarms are relevant, clear, and easy to understand.
- Alarms are configured consistently in accordance with industry best practice guidelines.

- Alarms are presented at a rate that the operator can effectively handle.
- Operators can rapidly assess the location and relative importance of all process alarms.
- Operators can process alarm information during high frequency alarm actuation events.
- Alarm systems are properly controlled, monitored, and maintained.
- Priority determination.
- Alarm handling methods.
- Operators are trained on the alarm management strategy.
- Alarm management enhances the operator's ability to make a judgment based on experience and skill.
- Operators will respond to all alarms, regardless of priority. So, the system design therefore must not produce more alarms than the operator can respond to.
- The alarm system is routinely maintained.
- Alarm management includes all categories of alarms coming to an operator, including system alarms.

According to Nimmo, if there is no guideline or cost for creation of alarms, poor practices will arise – such as all alarms enabled by default or set up by inconsistent rules of thumb, or set by an individual's preference shall be considered as poor practice. In Figure 5 one can see there has been an exponential growth of alarms per operator over the years; so, eventually practice of alarm management brings many standards and regulations to help manage the increasing alarm rate (Nimmo, 2006).

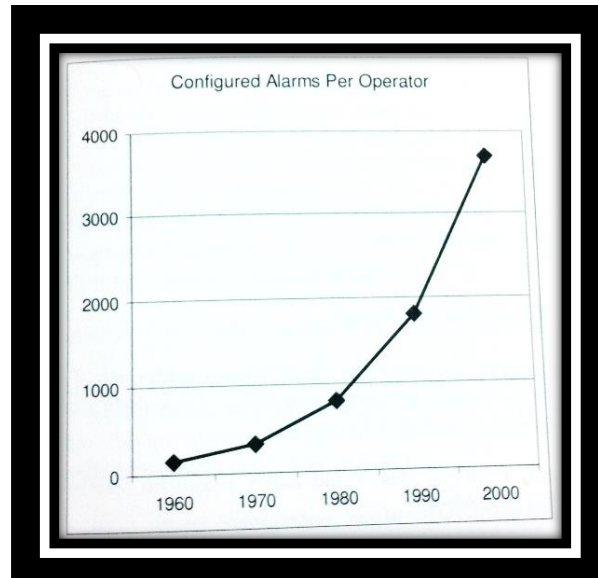


Figure 5: The number of Alarms per Operator has increased exponentially (Nimmo, 2006)

## Human Factor

Control system graphics are monitored by operators as much as 24 hours per day, so, ergonomics considerations are important. For operators ease, display graphics should be easy to read and they should understand the process flow clearly, so, the display graphic organization should be minimized to stop the data overloading to the operations. Operators have to make decisions and make adjustments quickly, so, the controlling manipulation should be really easy. Graphic elements and controls must behave and function consistently in all graphics and situations. The navigation should be logical and performance oriented. The entire alarm management display is a hierarchy of information prominence where alarms are the most prominent element.

The use of alpha numeric and text has been the traditional way of representing alarm list to operators (Errington et. al., 2006). In all systems in which the user's principal task is reading or processing text, legibility is the most important criterion (MacDonald, 1999). Good legibility can be acquired by adequate contrast between text and background. According to Stanton and

Stammers text messages are recommended for tasks requiring presentation of sequential information to be used (Stanton and Stammers, 1998). Esterby (1984) suggests seven psychological processes used by the human operator that should be considered in design of displays. He suggests that these processes determine the limits of the display formats. Table 1 explains the processes (Stanton and Stammers, 1998).

Table 2: Psychological processes and implications for design of visual alarm displays

Psychological process	implications for design of visual displays
Detection	Determining the presence of an alarm
Discrimination	Defining the differences between one alarm and another
Identification	Attributing a name or meaning to an alarm
Classification	Grouping the alarms with a similar purpose or function
Recognition	Knowing what an alarm purports to mean
Scaling	Assigning values to alarms
Ordering & Sequencing	Determining the relative order and priority of alarms

According to Easterby (1984) detecting an alarm easily should be the primary objective of designing an alarm management system. Understand the meaning of an alarm easily should be another attribute of an alarm management system. There are many methods that can be chosen while designing an alarm management system. Color is yet another important attribute considered as human factor while designing alarm management display. It can be said that color is one of the most effective visual attribute for coding information in displays and is capable, when used correctly, of achieving powerful and memorable effects (MacDonald, 1999). Color is the visual effect that is caused by the spectral composition of the light emitted, transmitted or

reflected by objects (Color Matters, 2011). Humans see color because of the emitted or reflected colored light rays from objects are captured by the human eyes, thus sending a message to brain to analyze. An object appears red to our eye because it absorbs all other colors light and only reflects visible red colors spectrum. There are three primary colors; red, green, and blue, and by combination of which produce a wide array of secondary colors such as yellow, cyan and magenta; and the combination of all three primary colors in appropriate intensities makes white (Abu Hassan et. al., 2012). When selecting colors certain rules or guidelines should be kept in mind. For highly critical alarms bright, highly saturated colors should be used as it helps to grab attention. The color conflicts are avoided as it is used for association and differentiation of a design's elements. If color is used excessively, it may hinder operator's ability to distinguish and prioritize between alarms, so, to improve the accuracy of visual judgment of a color, a neutral mid-gray surround or background is necessary, for avoiding unwanted perceptual color change. Symmetrical designs and layouts are used to minimize eye fatigue. Colors can be used effectively to distinguish between different categories, such as distinguishing different categories like high, medium, and low alarms in alarm management display. Appendix 6 explains the purpose of colors used on alarm management display system. Displays require a comparative low luminance because the observer directly views the display from a close distance, so, it is wise to use colors of low luminance in alarms with a high luminance background. Table 3 shows some colors and their luminance level (McDonald, 1999).

## **2.5 Summary and Hypotheses**

The alarm management system plays an important role in designing the safe and efficient SCADA system. Proper alarm management will result in improved safety, reliability, and overall profitability. It is physically impossible to properly analyze and respond to the alarm rates that

are commonly seen in industry if such alarm systems are not working. Human errors cannot be completely eliminated, but a good strategy or developed alarm management system can reduce the chance of errors. Designing a good alarm management system is very tedious job as there are too many variables, but research makes it possible to find the best possible practice. In today's environment, proper configuration and management of alarm system is not an option. It is part of the cost of doing business.

Table 3: Relative luminance ordering of computer graphics primary and secondary colors

Color	Relative Luminance (percent)
White	100
Yellow	90
Cyan	70
Green	60
Magenta	40
Red	30
Blue	10
Black	0

According to Hollifield (2007) it is becoming an increasing problem that there is no standard for plant operators yet, whereas improved design lead to a better performance. So, the objective of this experiment is to evaluate a better alarm display management system empirically. There are many methods to organize and build alarm display system. Different methods have been included in this experiment while designing different alarm displays, explained below.

Color has always been an effective way of showing alarms (MacDonald, 1999), different colors have different impacts on human eye and thus the right choice of colors for displaying alarms is one element to consider in finding a better alarm management system. Additionally, as Table 1 shows, Stanton and Stammer (1998) give importance on prioritization and organization



of alarms, which have impact on early detection of critical alarms. Predominantly, the color used for high priority alarms is red and yellow for caution or medium priority alarms. There are different opinions in the case of choosing color for low level priority alarms. Glen Uhack used white color as the color of low level alarms in his experimentation (Uhack II, 2010), but Hollifield (Hollifield et. al., 2010) suggested magenta color for low level alarms. Even the ABB review (Ragnal Aarliien et. al., 2004) suggested magenta as the low level alarm color.

This research will explore three different alarm interfaces that have been designed using different organization styles and minor color differences. The first display presents alarms in a chronological manner. The second display, a categorical display, groups alarms by priority. In both displays the latest alarm shows up at the bottom of the list and alarm background is color coded with red being a high alarm, yellow a medium alarm, and white a low alarm. The third alarm display differs from other two in all manners. It has a separate category for acknowledged alarms, which does not exist in other two displays and the latest alarm is presented at the top of the alarm list. Colors are the same except that the low priority alarms uses a magenta background different than the other two displays. Experimentation will be conducted to determine which display performs better for operators. Performance will be assessed by comparing response time, acknowledgement time and accuracy of response. This comparison gives us an insight on established three major hypotheses, and those are:

Hypotheses 1: There is a difference in response time or action time for operators based on the alarm interface type (Categorical Interface, Chronological Interface, and Revised Categorical Interface).

Hypotheses 2: There is a difference in acknowledgement time for operators based on the alarm interface type (Categorical Interface, Chronological Interface, and Revised Categorical Interface).

Hypotheses 3: There is a difference in user accuracy of response based on the alarm interface type (Categorical Interface, Chronological Interface, and Revised Categorical Interface).

There are subjective usability questions (Appendix 3), the results of which will be able to provide an overall idea on the usability (friendliness) of the system and difference between the three display interfaces.

## CHAPTER 3: EXPERIMENTAL DESIGN

To evaluate the impact of different alarm displays on operator performance, a between subject design was used to assess two different alarm rates (10 alarms and 20 alarms), three different alarm displays (Chronological, Categorical, and Revised Categorical), and three different alarm types (high, medium, low). Hence, the experimental model was used here  $3$  (alarm displays)  $\times$   $3$  (alarm types)  $\times$   $2$  (alarm rates). A liquid pipeline simulation experiment was developed and the participants ran the same display repeatedly at different alarm rate levels.

### 3.1 Extended Experiment

This experiment is an extension of a previous experiment done by Uhack (2010). This was a between subjects design where a participant was assigned to either the categorical display, chronological display, or revised categorical display. For the chronological and categorical displays, data was used from Uhack (2010) experiment. This thesis expanded that work by experimenting with a third display type, revised categorical. So, in this experiment participants worked on revised categorical display for 10 alarms in 10 minutes and 20 alarms in 10 minutes. The same set of alarms used in Uhack's experiment were used in this experiment for a fair comparison among three different alarm displays. Uhack's collected data for chronological and categorical displays and the data collected in this experiment for revised categorical display had been used together to analyze and reach a conclusion. The Participants that took part in this experiment were also exposed to all 3 displays for a subjective usability questionnaire.

The main objective of this experiment was to evaluate a third type of display on controller response as highlighted in table 4 and compare its results to previous work conducted by Uhack (2010). Each of the criteria used in three alarm displays are shown in the Table 4.

Table 4: Criteria used for different Alarm Displays

Criteria	Chronological Alarm Display	Categorical Alarm Display	Revised Categorical Alarm Display
High Alarms – Red	Yes	Yes	Yes
Medium Alarms – Yellow	Yes	Yes	Yes
Low Alarms – White	Yes	Yes	No
Low Alarms – Magenta	No	No	Yes
Chronological Order	Yes	No	Yes
Categorical Order	No	Yes	Yes
Separate list for Acknowledgement Alarms	No	No	Yes

Methods used for the revised categorical alarm display experiment mirror the methods used by Uhack (2010) and will be discussed in detail below.

### 3.2 Experimental Method

The experiment is designed to collect the data and measure the performance of pipeline and refinery control room operators who are responsible for monitoring the transportation of different liquidated products through the pipelines. The performance of the participants during the operation and the actions taken by the participants while handling the alarmed situation were recorded. Participants completed two separate experiments lasting ten minutes each. Each experimental display includes one pipeline window, detail station screens and an alarm window. The revised categorical alarm displayed alarms categorized by priority using color and within group sorting. Three priority levels were used: Red color-High, Yellow color-Caution, and Magenta color-Low.

Alarm rate/interval during each experiment was evenly distributed given any number of alarms. For example, in a set of 10 alarms, one alarm were fired every minute during the 10 minutes time period. Same set of 10 alarms were used throughout the experiment. For the 20 alarms in 10 minutes two alarms were fired every minute. And same set of 20 alarms were used throughout the experiment.

The experimental scenarios completed by participants were randomized.

### 3.3 Independent Variables

The independent variables used in this study included alarm rates (10 and 20 alarms per 10 minutes), alarm display, and alarm priority (high, medium, and low). Each is discussed below.

- Alarm Rates:

Two different alarm rates were used for this experiment. In determining the alarm rates to be evaluated, EEMUA 191 and ISA 18.2 alarm standards were taken into consideration and are found in Appendix 4 and Appendix 5. Table 5 represents alarm rates used for this particular study based on alarm rate principles from a previous study (Uhack, 2010).

Table 5: Alarm Rates Used for Experiment

Alarm rate	Experimental display		
	Chronological	Categorical	Revised Categorical
20 in 10 minutes			
10 in 10 minutes			

- Alarm Priority:

Figure 6 shows the distribution of alarm types used in the two experimental conditions. While not possible to evenly distribute the alarms given the experimental alarm rates, the high

and medium alarms were made equal and the reduction in alarms was taken from the low priority alarms.

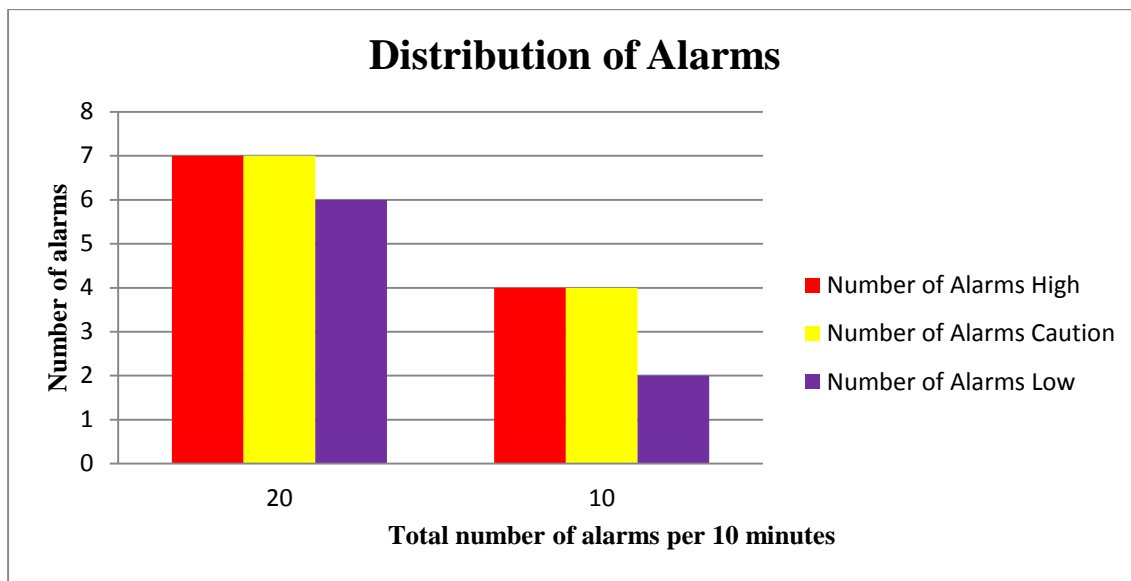


Figure 6: Alarm Priority Distribution

- Alarm Window:

Three types of different alarm windows used as, Chronological Alarm Display, Categorical Alarm Display, and Revised Categorical Alarm Display. All three displays are described here were for the complete analysis however this experiment only used the revised categorical alarm display. The alarm displays are shown in the Figures 7, 8, and 9.

Chronological Alarm Display: Alarms come one after another chronologically; firing alarms do not depend on the colors but solely on the time. The most recent alarm comes at the bottom of the list. Three different colors red, yellow, and white, were used for high, medium, and low alarm types respectively.

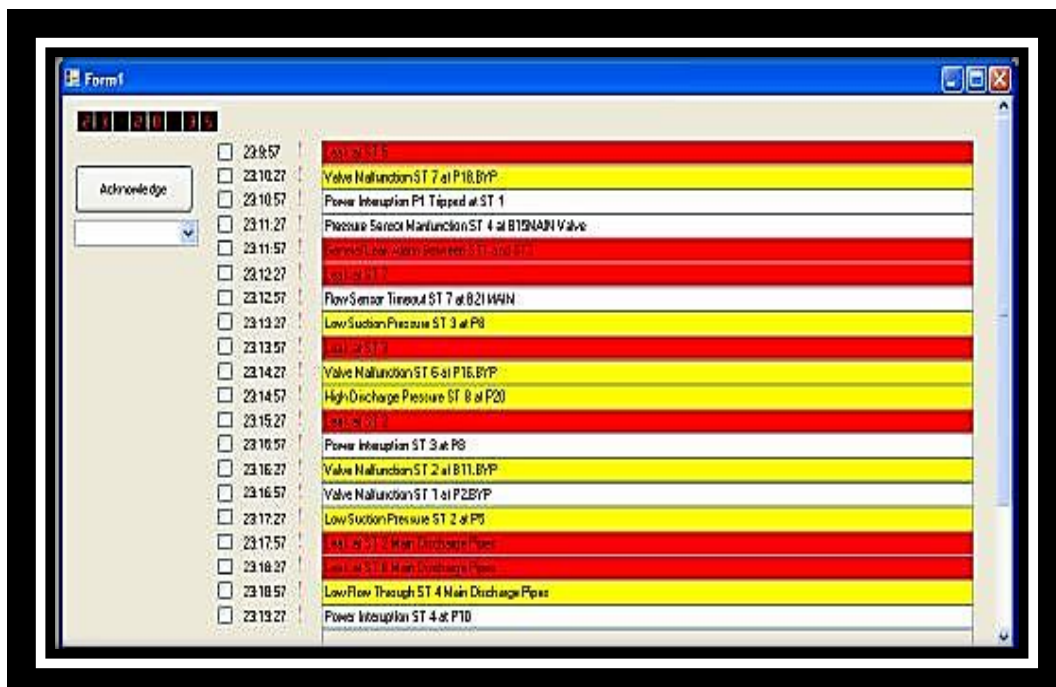


Figure 7: Chronological Alarm Display

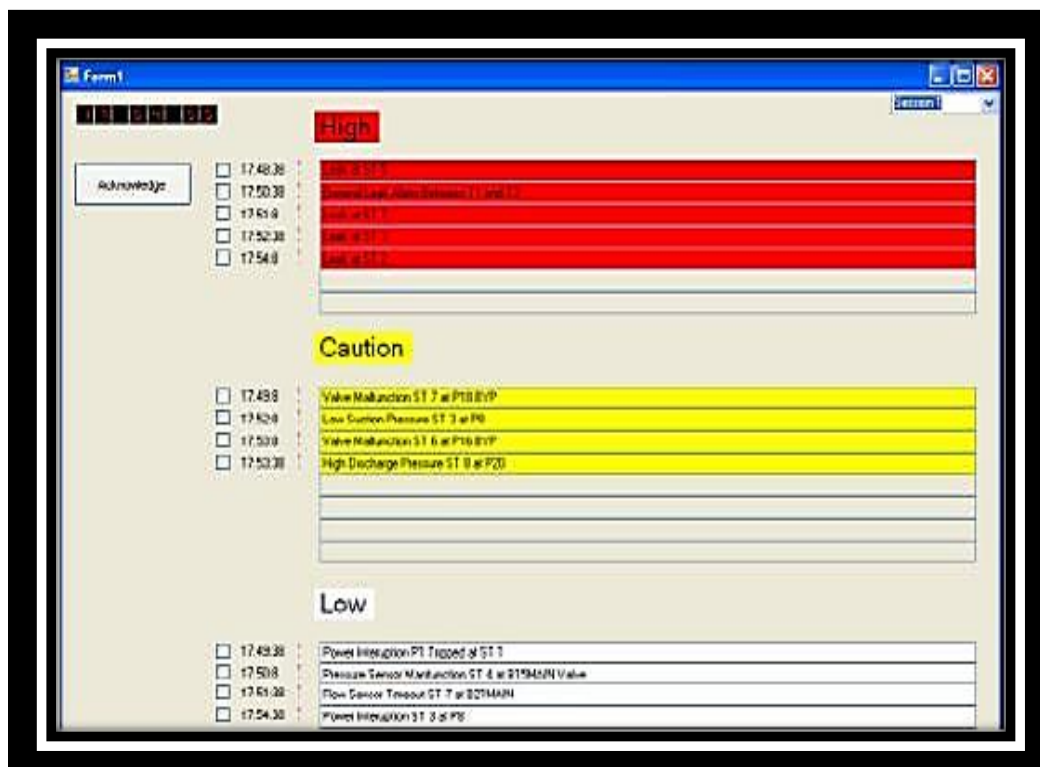


Figure 8: Categorical Alarm Display

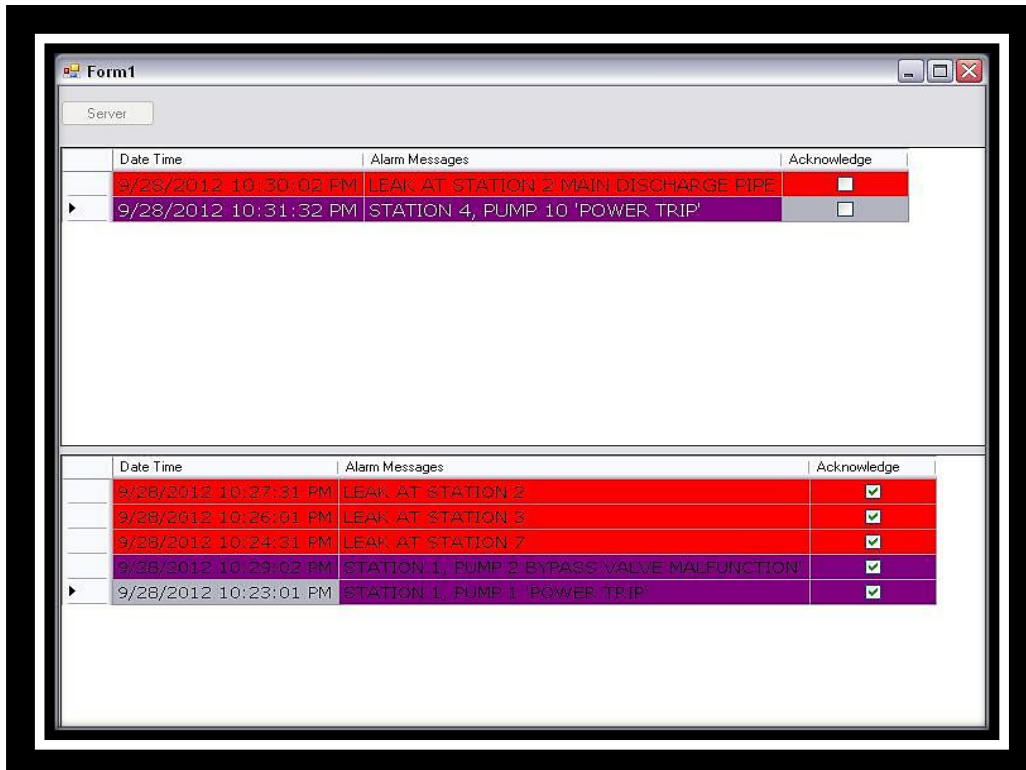


Figure 9: Revised Categorical Alarm Display

Categorical Alarm Display: Alarms come one after another categorically. There are three different color codes; red-high (highest level critical alarms), yellow-caution (medium level critical alarms), white-low (lowest level critical alarms). Depending on colors there are three different lists. The same colored alarms shall gather at one list and the latest alarm appears at the bottom of each list, which means it does not depend on time and solely depends on color. After the acknowledgement the alarms turns into gray color and remain at the same place.

Revised Categorical Alarm Display: Alarms come one after another following both category and color. This display has only one list but same colored alarms are populated at one place in the list, but it follows the chronological manner as well, so, the most recent alarm appears at the top of each color wise piled alarms depending on the color. Acknowledged alarms disappear from the raised-alarm list and appears at the bottom in a separate list following both category and color. There are three different color codes; red-high (highest level critical alarms),



yellow-caution (medium level critical alarms), magenta-low (lowest level critical alarms). The background color is used as white, which has high relative luminance (Table 2).

### **3.4 Dependent Variables**

A display capturing software, MORAE<sup>®</sup> (TechSmith at Okemos, MI, USA) has been used to record the actions of participants during experiment. Alarm appearing time, task completion time, and alarm acknowledgement time are recorded and used to collect the dependent variables.

- **Response Time:** Time taken by a participant to initiate an action after an alarm is raised to eliminate the alarmed condition. Difference between alarm appearing time and task completion time.
- **Acknowledge Time:** It is the time taken by a participant to acknowledge the alarm, after it gets displayed on the alarm window. Difference between alarm appearing time and acknowledgement time.
- **Accuracy of response:** This variable is used to track if operator took the proper set of action(s) in handling the alarms. Every task has a set of actions to complete. If participants take same set of actions to complete that particular task, then it is considered as accurate and will be marked as numeric one, and if the task is not performed correctly, it will be marked as numeric zero. So, the accuracy of response can be determined from the binary numbers.

### **3.5 Experimental Participants**

Thirty-one (31) college of engineering student participants from Louisiana State University ranging in age from 20 to 28 (average age was 23, 33 male, 4 female) participated in the experiment. The total number of potential participants was thirty seven (37), and out of thirty seven a total of thirty one (31) participants' data were used as the sample dataset. Six participants

were rejected using the rejection criteria. Selection and rejection participants chart can be found at appendix 7, and the process is described in the following section.

Detailed demographic survey information was collected and the survey questionnaire can be found in Appendix 1. All participants were given training about abnormal situation principles and a navigational tour of the designed pipeline system before starting the experiment. Participants were given a demonstration and a practice session to understand the simulation. After completing the demonstration session and practice session, participants were asked to complete a quiz questionnaire that can be found in Appendix 2. The experiment was not started until the participants felt comfortable with the system. All experiments were randomized. After all experiments, each subject had to work on other two displays (Chronological and Categorical displays) similarly the way they worked on revised categorical display. Then provided a subjective usability questionnaire to express their views on different display types.

### **3.6 Participant Training and Selection Criteria**

To reduce differences among participants, all participants completed a training/demonstration session, familiarization session, a multiple-choice quiz, and training qualification assessment. The quiz questionnaire (Appendix 2) was prepared by following the guidelines given in the experiment completed by Uhack (2010). For participant selection process some specific criteria were considered described below.

Computer skill – 3 or more in a rating system of 1 to 5. Participants had a fair amount of hands-on experience with computer handling (Appendix 1).

Video game – sometimes or never. It is better to choose people who are not too familiar with animated application, as it will test their adaptability with the designed pipeline system and alarm management system (Appendix 1).

Hydraulic software use – No. To ensure all participants were on equal footing, no students with hydraulic software experience were used as participants (Appendix 1).

Quiz score – Students had to perform more than eighty percent score on the quiz to be considered as acceptable (Appendix 2).

This pre-experiment training and testing was developed to help ensure only those participants who are able to successfully execute tasks representative to those during the actual experiment would be allowed to complete the experiment.

### **3.7 Apparatus**

Stoner Pipeline Simulator (Advantica at Carlisle, PA, USA) was used to develop a pipeline model that calculated the fluid hydraulics and transients occurring in the simulated pipeline. SPS is widely used in the pipeline community for engineering analysis. Advantica's interface design module for SPS, in conjunction with Microsoft Visual Studio.Net 2008/2010, was used to develop the graphical user interface (GUI) for the pipeline model that was used in the experiments. Different alarm windows were created using Visual Basic programming, and alarms presented to participants were driven by the rules of SCADA systems defined by PHMSA (2008) for different abnormal process situation (e.g. pressure, flow, and temperature). Sample pictures of the user interfaces are provided in Figures 10, 11, and 12.

The study utilized four computer monitors, one 27 inches display, and three 19 inches display. The 27-inch monitor was used to display the participant qualifying and experiment overview displays. Two 19-inch monitors were used to display detailed station displays of the simulated pipeline system. The remaining 19-inch monitor was used to display the alarm window and maintenance request form. Special hardware was used so that one keyboard and mouse could control all system functions. A picture of the hardware setup is provided in Figure 13.

MORAE<sup>®</sup> (video capturing software) was used to capture each participant's performance during the experimental scenarios, and installed on the same computer used for the study. The captured data was used for analyzing and finding conclusion later.

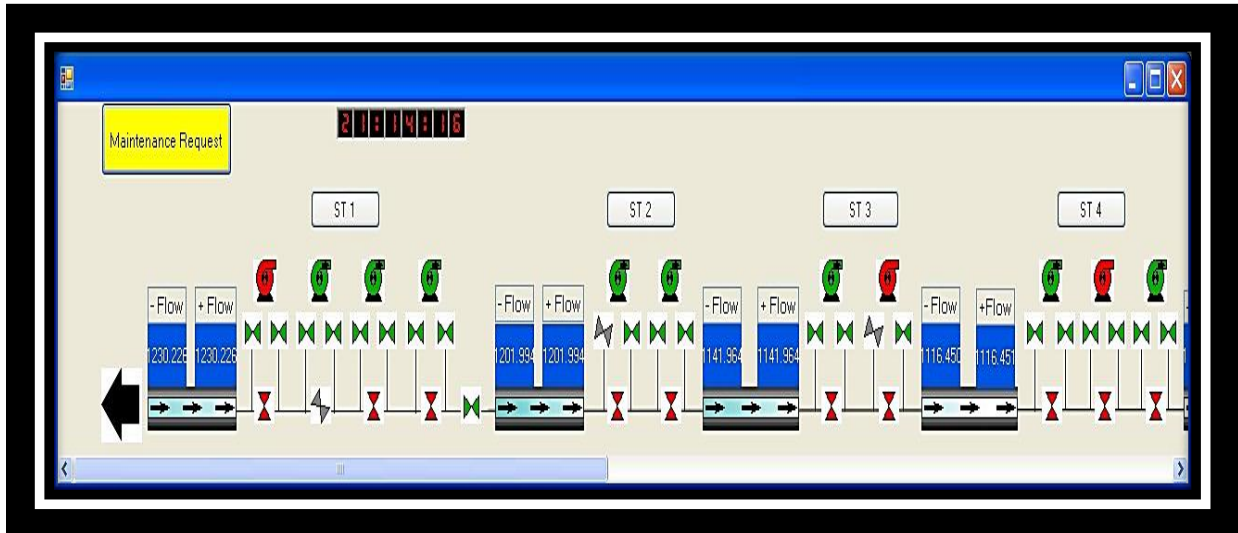


Figure 10: Partial Snapshot of Overview Display Used During Actual Experiment

Form1			
Server			
Date Time	Alarm Messages	Acknowledge	
9/28/2012 10:30:02 PM	LEAK AT STATION 2 MAIN DISCHARGE PIPE	<input type="checkbox"/>	
9/28/2012 10:31:32 PM	STATION 4, PUMP 10 'POWER TRIP'	<input type="checkbox"/>	
Date Time	Alarm Messages	Acknowledge	
9/28/2012 10:27:31 PM	LEAK AT STATION 2	<input checked="" type="checkbox"/>	
9/28/2012 10:26:01 PM	LEAK AT STATION 3	<input checked="" type="checkbox"/>	
9/28/2012 10:24:31 PM	LEAK AT STATION 7	<input checked="" type="checkbox"/>	
9/28/2012 10:29:02 PM	STATION 1, PUMP 2 BYPASS VALVE MALFUNCTION	<input checked="" type="checkbox"/>	
9/28/2012 10:23:01 PM	STATION 1, PUMP 1 'POWER TRIP'	<input checked="" type="checkbox"/>	

Figure 11: Example of Revised Categorical Alarm List Display

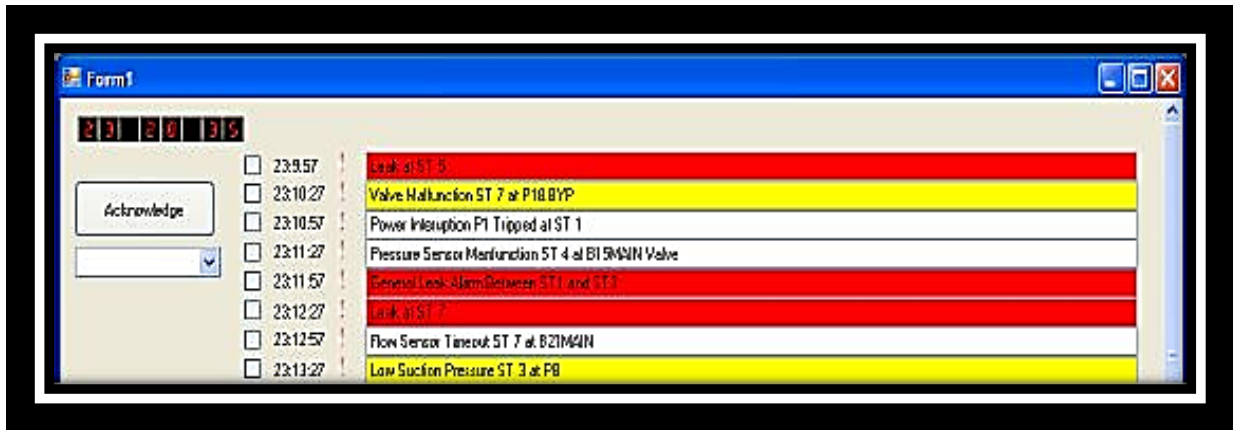


Figure 12: Example of Chronological Alarm List Display

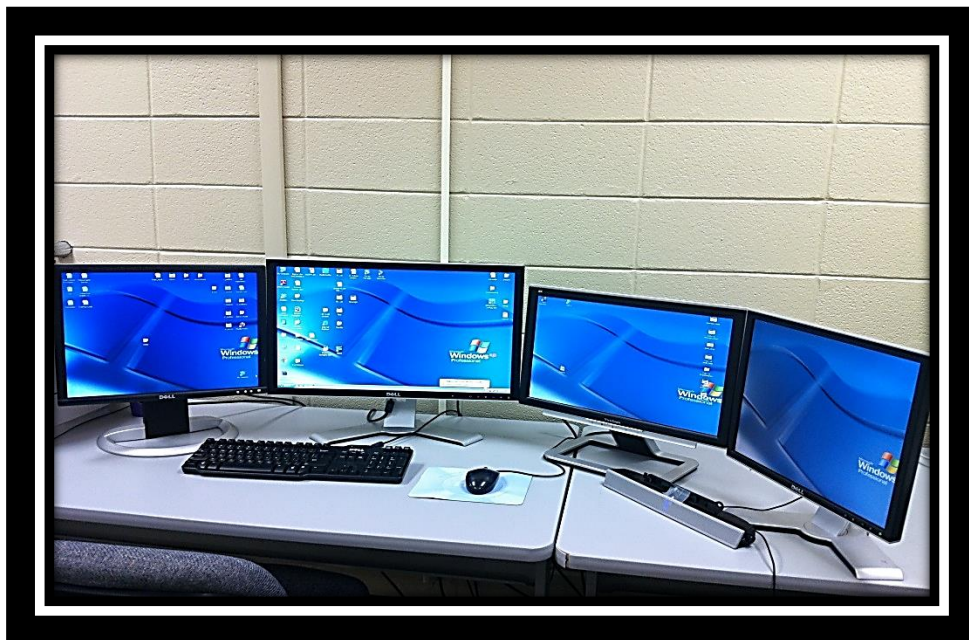


Figure 13: Lab Setup

### 3.8 Procedure

Since this experiment involved human participants, an Institutional Review Board (IRB) approval was filed and exemption number, E4665, was received. The participant consent form, can be found in Appendix 9. All participants had to complete a demographic survey (Appendix 1) in the beginning of the experiment. Then they were given training which included a PowerPoint presentation (Appendix 17), training/demonstration session, familiarization session,

and a general knowledge quiz. A demonstration session was used to train participants on the pipeline system and basic components like pump, valve and their working principles. Then there was familiarization session where they get an overall idea on navigation and fundamental principle of abnormal situation assessment and responses required for each type of abnormal event simulated in this experiment. After that, participants were tested on their understanding about pipeline system with a general quiz. Participant selection process was the same as followed in the experiment done by Uhack (2010). Participants were eliminated if they had a prior experience with the Stoner Pipeline System simulation and if they had extensive computer gaming experience. The selected participants had to score at least 7 out of 9 on the general quiz and they needed computer skill at least 3 out of 5.

As a response to every alarm, there were certain tasks required such as identifying the abnormal situation, assess the situation and take necessary steps. Action had to be taken on every alarm and all alarms are distributed among three different priority levels as high, caution, and low. High alarms, few in number, are there to indicate a failure of an operator could result in a person getting hurt. For an instance, any leak at any station is considered as high priority alarm. Failure of an important device's redundant power supply or uninterruptible power source malfunction is considered as caution level priority. Bad value alarms are considered as low priority alarms, as for example flow sensor timeout, pressure sensor failure. Detailed list of alarms can be found in Appendix 9 and in Appendix 10. So, participants were given instruction that high level alarms needed to be taken as the highest priority, following the medium level alarms, and at the last the low level alarms.

The participants completed experiments and their performance was recorded using the MORAE<sup>®</sup> software. The experimental scenarios completed by participants were randomized.

Specifically, the order in which participants were randomly assigned to an alarm rate and then experience all alarm types using the revised categorical. At the end of the experiments, participants were exposed to all three types of displays and completed a subjective usability questionnaire, which can be found in Appendix 3.

## CHAPTER 4: ANALYSIS AND RESULTS

The analysis of variance (ANOVA) method was used to test if the differences in the participants' performance statistically significant for each experiment by analyzing the performance measures (e.g. acknowledge time, response time, accuracy of response) which were collected from the experiment. Tukey-Kramer mean test were used to find the differences between different groups.

Using the two display data from Uhack (2010) and additional display type (Revised categorical display), the analysis is a  $3 \times 3 \times 2$  model. For the experiment three different display types, three different alarm types, and two different alarm rates are used. The interaction between different groups will help to understand the impact of acknowledge time and response time, and help to draw a conclusion. Three different hypothesis were formed and explained in a previous section to draw conclusion from the experimental results, and they are analyzed statistically, using SAS 9.3 statistical tool. All hypothesis will be tested at 0.05 significance level.

Descriptive result tables could be found at Appendix 12. Results show that the performance of the participants in terms of response time is affected by the alarm display types. Figure 14 shows the mean response time of participants for different display types, different alarm types, and different alarm rates. It can be seen that though participants' performance do not vary much for the alarm rate of 10 alarms in 10 minutes, there is a distinguished difference for 20 alarms in 10 minutes. It was noticed during the experiment that with increasing alarm rate a stack of unresolved alarms usually formed in the alarm list, and this scenario was very common during the experiment of 20 alarms in 10 minutes, as it violates the EEMUA No.191 average alarm rate standard (Appendix 4). Participants had to work on a stack of alarms. Figure 14 shows that participants dealt with more ease on stacked alarms when they had to work on revised



categorical display type. There is a clear difference can be seen between categorical display and chronological display, and categorical display resulted better over chronological display. Between categorical and revised categorical display types there is not much difference noticed for alarm rate of 10 alarms in 10 minutes, but the difference is noticeable for the alarm rate of 20 alarms in 10 minutes. A different color was used in the revised categorical display for the low level alarms. Figure 14 appears to show a difference between categorical display and revised categorical display for the low level alarms.

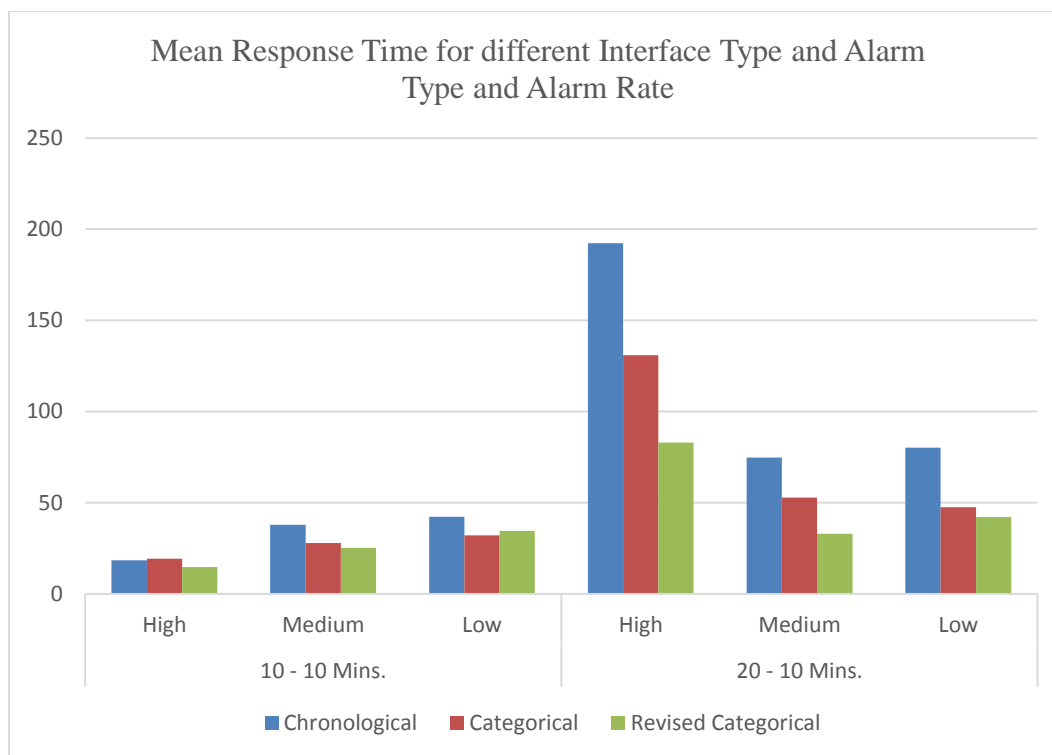


Figure 14: Graphical representation of Mean Response Time for different Interface Types, Alarm Types, and Alarm Rates

Figure 15 shows the mean acknowledge time of participants for different display types, different alarm types, and different alarm rates. It can be seen that though participants' performance do not vary much for the alarm rate of 10 alarms in 10 minutes there is a distinguished difference for the 20 alarms in 10 minutes. As explained previously that

participants had to work on stacked alarms, Figure 15 shows that participants dealt with more ease on stacked alarms when they had to work on categorical display type. There is a clear difference can be seen between categorical display and chronological display, and categorical display resulted better over chronological display. Between categorical and revised categorical display types there is not much difference noticed for alarm rate of 10 alarms in 10 minutes, but the difference is noticeable for the alarm rate of 20 alarms in 10 minutes.

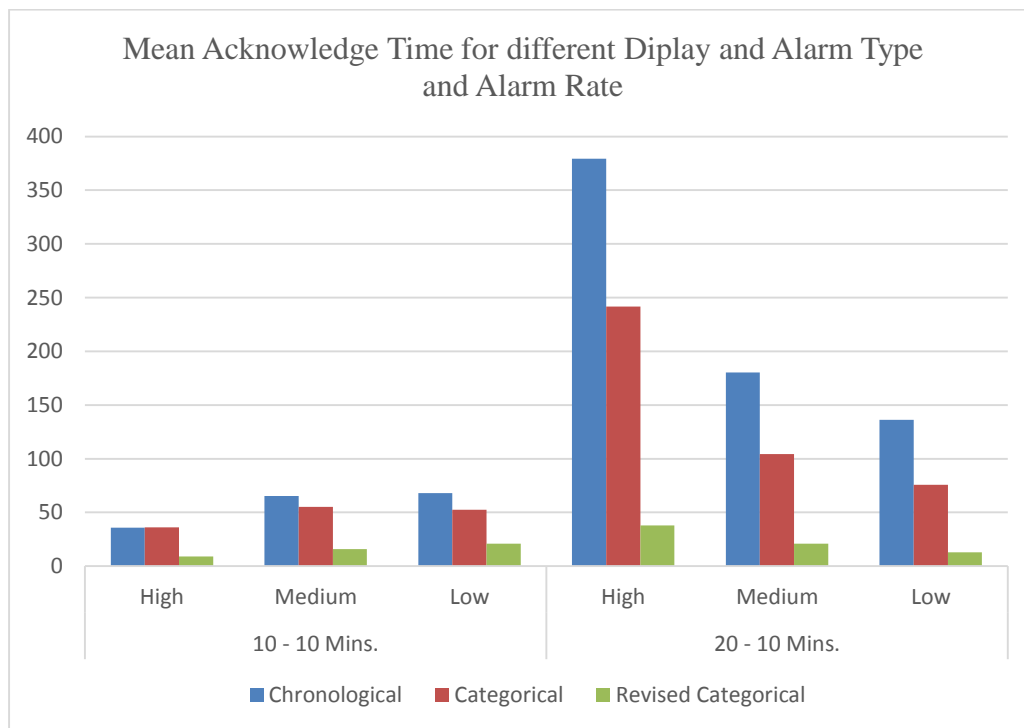


Figure 15: Graphical representation of Mean Acknowledge Time for different Interface Types, Alarm Types, and Alarm Rates

Figure 14 shows that there clearly is a difference between categorical display and revised categorical display for the low level alarms, so, it may be that participants felt more at ease working with the form of interaction used in the revised categorical display. From the above discussion it can be clearly understood that different display types have impact on participants' performance pertaining to the response time.

Table 6 shows the percentage of the tasks accurately done by participants for different displays. Participants performed most accurately on revised categorical display, as the accuracy percentage is the highest (98.92%). So, it can be concluded that participants felt at ease while working on revised categorical display and performed best on it.

Table 6: Participants' performance accuracy percentage chart for Display Type

Display Type	Correct tasks	Total no. of tasks	Percentage of accuracy
Chronological	888	930	86.44%
Categorical	894	930	96.13%
Revised Categorical	920	930	98.92%

Table 7 shows the percentage of the tasks accurately done by participants for different alarm types. Participants performed most accurately for medium alarm type, as the accuracy percentage is the highest (97.75%). So, it can be concluded that participants felt at ease while working on lower alarm rate.

Table 7: Participants' performance accuracy percentage chart for Alarm Type

Alarm Type	Correct Tasks	Total number of Tasks	Percentage
High	996	1023	97.36%
Medium	1000	1023	97.75%
Low	706	744	94.89%

From the accuracy of response analysis participants performed best for the revised categorical display. Figure 16 and above bar-charts show participants liked and performed best on the revised categorical display. Revised categorical interface stands out from other two displays on many prioritization approaches. Not only the appearing of alarms are different in this display, but the alarm color coding is also little different than other two displays. The statistical

test results (explained below) helping us to make a clear notion if prioritization techniques have an impact on participants performance.

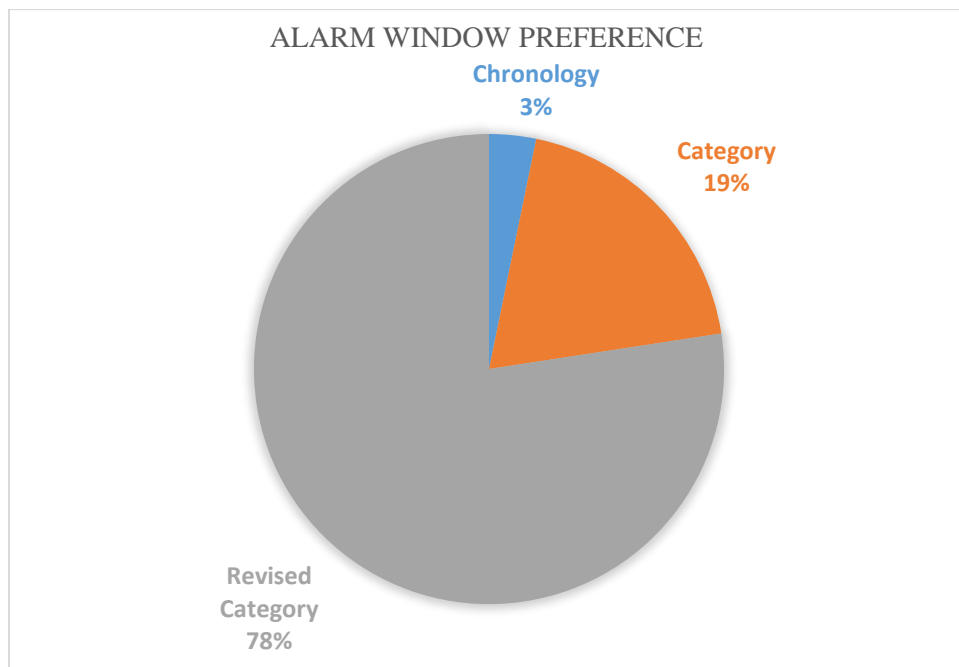


Figure 16: Participants' likeness pie-chart for different alarm displays

#### Hypothesis 1

Null Hypothesis  $H_0$  : No differences exist in participant's response time across the interactions between display types, alarm types, and alarm rates, where the display types, alarm rates, and alarm types are given.

Alternate Hypothesis  $H_1$  : Differences exist in participant's response time across the interactions between display types, alarm types, and alarm rates, where the display types, alarm rates, and alarm types are given.

Dependent Variable: Response Time

Independent Variable: Interface Types (Chronological, Categorical, Revised Categorical),

Alarm rate (10-10, and 20-10), Alarm types (High-1, Medium-2, Low-3)

## Model Assumptions

First the residuals from the model was considered to check the assumptions of ANOVA. A statistical test was performed to examine the spread of the residuals to see if the variance was constant for each of 18 groups and if the residuals were normal, as, they were the assumptions of ANOVA.

To test the homogeneity of variances assumption, normality of residuals were plotted by the residuals of fitted values. Figure 14 is the plot of residuals by the fitted values. Each predicted value (A, B, C, F, etc.) represents one of the 18 separate groups. A common scatter or a band like shape of the residuals for each predicted value is the ideal condition, because it will meet the criteria of having homogeneity of variance, which is an assumption of ANOVA test. Figure 17 shows that there might be a possible problem with homogeneity of variance for the groups, as fitted values are scattered and not forming any band shape.

Another assumption of ANOVA is the residuals are normally distributed, so, an analysis was run on the residuals specifically looking at the comparison to the normal quantiles, and the histogram of the residuals. The residuals for ANOVA with response (Figure 18) appeared to have a significant departure from the normal quantiles, and when looked at the histograms, it was not bell shaped. As the bell shaped histogram reflects that residuals are normally distributed, this scenario predicts that the collected data were not normally distributed.

Since the data was not normally distributed, a logarithmic transformation was performed that produces a residual plot where the residuals appear to not show any specific pattern. Figures 19 and 20's transformed data seems to indicate that the homogeneity of variance and normality assumptions are no longer violated.

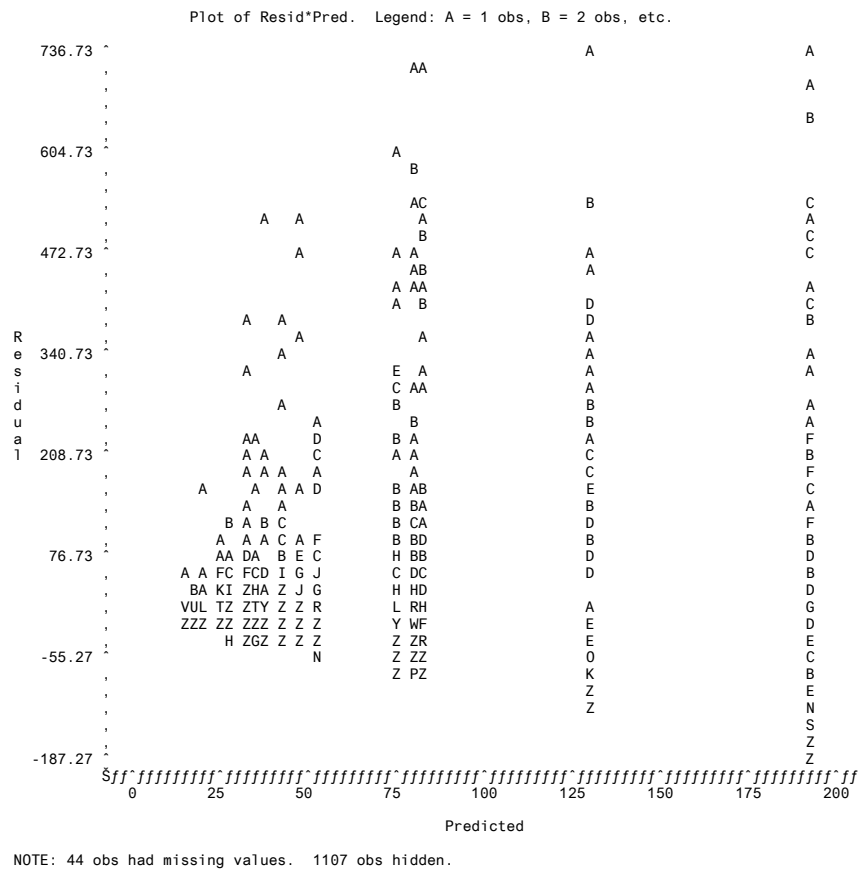


Figure 17: ANOVA w/proc Mixed Normality of residuals test plot of residuals by fitted values before transforming Response Time data to Log values

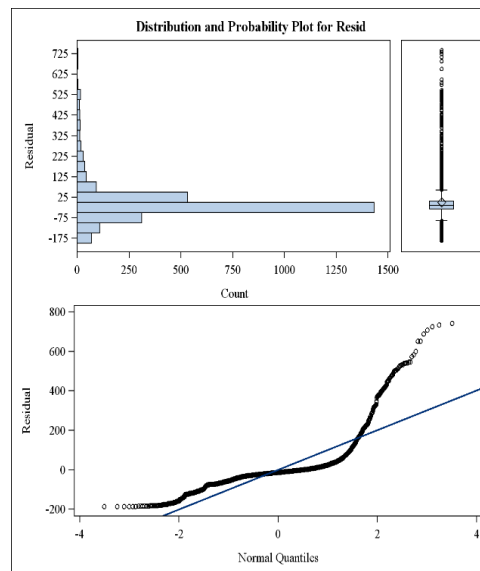


Figure 18: Residuals for ANOVA with response

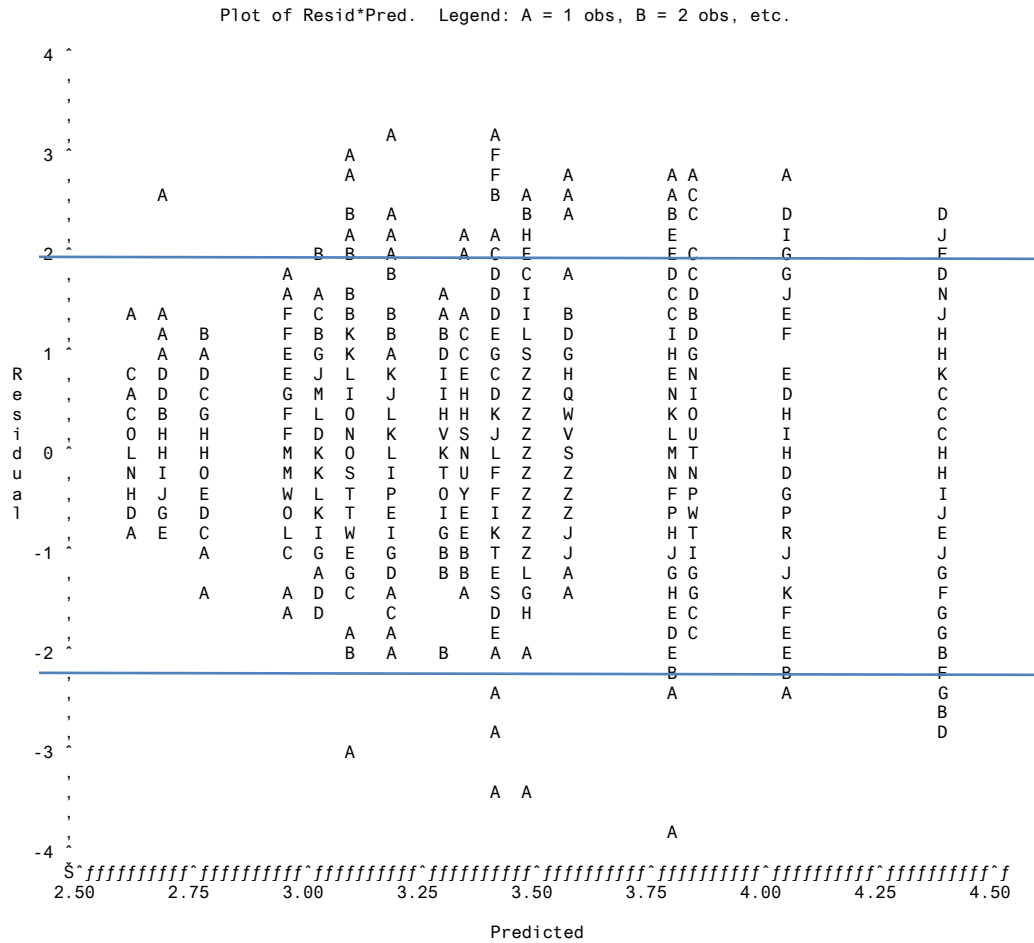


Figure 19: ANOVA w/proc Mixed Normality of residuals test plot of residuals by fitted values after transforming Response Time data to Log values

#### Hypothesis 1 Analysis:

Table 8 provides information on different interactions between display types, alarm types, and alarm rates. The interaction of display types and alarm rates was significant ( $F = 13.32$ ,  $p\text{-value} = .0001$ ). Following the same, it can be said that the interaction between display types and alarm types is also statistically significant ( $F = 2.38$ ,  $p\text{-value} = 0.05$ ). Interaction across alarm rates and alarm types is also statistically significant ( $F = 50.27$ ,  $p\text{-value} = 0.0001$ ). So, it can be concluded that response time has statistically significant effect on different interactions between display types, alarm rates, and alarm types although there is not a 3-way interaction.

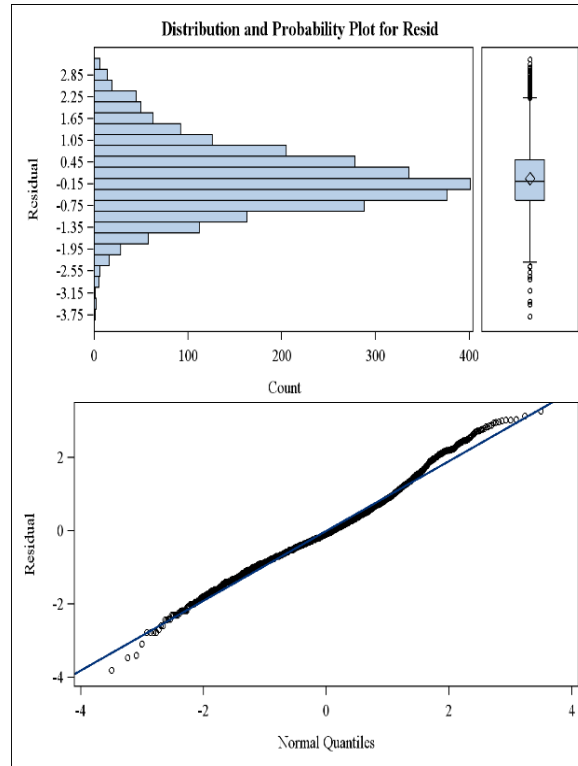


Figure 20: Residuals for ANOVA with log response

Table 8: Factorial ANOVA Proc-Mixed output for all main effects and interactions (\*  $P \leq 0.05$ )

Effect	Num DF	Den Df	F value	Pr > F
Display	2	2673	39.80	<.0001 *
Rate	1	2673	251.04	<.0001 *
Type	2	2673	16.63	<.0001 *
Display*Rate	2	2673	13.32	<.0001 *
Display*Type	4	2673	2.38	0.0500 *
Rate*Type	2	2673	50.27	<.0001 *
Display*Rate*Type	4	2673	1.45	0.2161

For each significant interaction, the LS Means or Least Square Means (Estimate values) Tukey-Kramer means test was performed to find which groups were different from one another. Different letter groupings explain differences between two groups are statistically significant.

#### Display Type and Alarm Rate Interaction Analysis

Table 9 shows the interaction across display types and alarm rate depending upon the participants' response time. It helps to compare between displays depending on the alarm rates. It



can be seen that response time for different alarm rates have differences, and it is statistically significant as the letter grouping is different.

From the estimate values it can be predicted that the overall performance of participants for 10 alarms in 10 minutes were better than the overall performance of participants for 20 alarms in 10 minutes. But there is a common letter grouping, which is 'C', can be seen among the alarm rate of 10 alarms in 10 minutes, which projects that the differences among different display types for alarm rate of 10 alarms in 10 minutes are not statistically significant.

Significant differences can be found in case of alarm rate of 20 alarms in 10 minutes, as the letter groupings are for chronological, categorical, and revised categorical displays are different and they are 'A', 'B', and 'C' respectively. Participants performed best for the display type revised categorical for both 10 and 20 alarms rate.

Table 9: Interaction between Display Type and Alarm Rate

Display	Rate	Estimate	LSMean in Seconds	Letter group
Chronological	20	4.0119	55	A
Categorical	20	3.6909	40.08	B
Revised Categorical	20	3.3213	27.69	C
Chronological	10	3.1502	23.34	CD
Categorical	10	3.0013	20.11	D
Revised Categorical	10	2.9607	19.31	D

From letter groupings, it was found that alarm rate 10 in 10 minutes is not statistically significant but alarm rate 20 in 10 minutes is statistically significant. Interestingly, the letter groupings showed that there was no significant participants' performance difference between revised categorical display for 20 alarms in 10 minutes and chronological display for 10 alarms in 10 minutes. It is an interesting finding and helps to conclude that alarm display can make an impact on human performance.

## Display Type and Alarm Type Interaction Analysis

Table 10 shows the interaction across display and alarm type depending upon the participants' response time. Estimate values can help to compare interfaces depending on alarm types, which are high-1, medium-2, and low-3. It can also be predicted if those differences are statistically significant from the letter groupings.

Table 10: Interaction between Display Type and Alarm Type

Display	Alarm Type (high-1/medium-2/low-3)	Estimate	LS Mean in Seconds	Letter Group
Chronological	3	3.6696	39.24	A
Chronological	1	3.5785	35.81	AB
Chronological	2	3.4950	32.95	AB
Categorical	3	3.4335	30.98	ABC
Revised Categorical	3	3.4012	30	BC
Categorical	1	3.3625	28.86	BC
Categorical	2	3.2423	25.59	CD
Revised Categorical	2	3.0201	20.49	D
Revised Categorical	1	3.0018	20.12	D

In case of high-1 priority alarms, there is no statistically significant difference exist between the interface types chronological and categorical, but statistically significant difference exist for the interface type revised categorical. As the letter grouping of chronological type is 'AB' and letter grouping of categorical type is 'BC', both have a common letter which is 'B', so, chronological and categorical display are not statistically significantly different. The estimate value of categorical type (3.3625) is lower than the estimate value of chronological type (3.5785), so, it can be concluded that participants responded well for categorical type interface but not statistically significantly. The estimate value of revised categorical type (3.0018) is the lowest and has letter grouping 'D', so, it can be concluded that participants performed best on revised categorical display for high-1 priority alarm type and it is statistically significant.

In case of medium-2 priority alarms, the letter groupings for interface types chronological, categorical, and revised categorical are 'AB', 'CD' and 'D' respectively. So, it can be concluded that the difference between chronological display and categorical display is statistically significant. The difference between chronological display and revised categorical display is also statistically significant. But the difference between categorical display and revised categorical display is not statistically significant. Between the estimate values of the three display types, it is found that the revised categorical display has the lowest value, which is 3.0201. So, it can be concluded that participants performed best on revised categorical display for the medium-2 type alarms.

In case of low-3 priority alarms, the letter groupings for interface types chronological, categorical, and revised categorical are 'A', 'ABC' and 'BC' respectively. So, it can be concluded that the difference between chronological display and revised categorical display is statistically significant. The difference between chronological display and categorical display is not statistically significant. And the difference between categorical display and revised categorical display is also not statistically significant. Among the estimate values of the three display types, revised categorical display has the lowest value, which is 3.4012. So, it can be concluded that participants performed best on revised categorical display for the low-3 type alarms.

Participants' performance on chronological display had no significant difference between all alarm types, and the performance were worst among all three different alarm displays. Interestingly, participants' performance on revised categorical alarm display for low alarm type had no significant difference from chronological display (high and medium alarm types) and categorical display (high, medium and low alarm type). Hence, this finding supports the notion

that alarm display can impact and improve the human performance. In case of critical alarms or high level alarm type, participants' performed best on the revised categorical display.

#### Alarm Rate and Alarm Type Interaction Analysis

Table 11 shows the interaction between alarm rates and alarm types. For low priority alarm - 3 is statistically significantly different, as it has a letter grouping 'B', which is different among all interactions. Interaction of alarm rate 20 and medium priority alarm - 2 is not statistically significantly different than the interaction of alarm rate 10 and low priority alarm - 3. From the estimate values it can be concluded that participants performed better for alarm rate of 10. It is also noticeable that for low priority alarm - 3, participants have performed better than high priority alarms - 1, where alarm rate 20 is considered.

Table 11: Interaction between Alarm Rates and Alarm Types

Rate	Type	Estimate	LS Mean in Seconds	Letter Group
20	1	3.9390	51.37	A
20	3	3.6309	37.75	B
20	2	3.4542	31.63	C
10	3	3.3720	29.14	C
10	2	3.0507	21.13	D
10	1	2.6895	14.72	E

#### Hypothesis 2

Null Hypothesis  $H_0$  : No differences exist in participant's acknowledge time across the interactions between display types, alarm types, and alarm rates, where the display types, alarm rates, and alarm types are given.

Alternate Hypothesis  $H_1$  : Differences exist in participant's acknowledge time across the interactions between display types, alarm types, and alarm rates, where the display types, alarm rates, and alarm types are given.

Dependent Variable: Acknowledge Time

Independent Variable: Interface Types (Chronological, Categorical, Revised Categorical),  
Alarm rate (10-10, and 20-10), Alarm types (High-1, Medium-2,  
Low-3)

#### Model Assumptions

Similarly, like the previous hypothesis the model had three display types, three alarm types and two alarm rates, so, the model was to be analyzed would have ( $3 \times 3 \times 2 =$ ) 18 different groups.

Residuals from the model was considered to check the assumptions of ANOVA. A statistical test was performed to examine the spread of the residuals to see if the variance was constant for each of 18 groups and if the residuals were normal, as, they were the assumptions of ANOVA.

To test the homogeneity of variances assumption, normality of residuals were plotted by the residuals of fitted values. Figure 18 is the plot of residuals by the fitted values. Each predicted value (A, B, C, F, etc.) represents one of the 18 separate groups. A common scatter of the residuals for each predicted value is the ideal condition, because it will meet the criteria of having homogeneity of variance, which is an assumption of ANOVA test. Figure 21 showed that there might be a possible problem with homogeneity of variance for the groups, as fitted values are scattered and not forming any band shape.

Another assumption of ANOVA is the residuals are normally distributed, so, an analysis was run on the residuals specifically looking at the comparison to the normal quantiles, and the histogram of the residuals. The residuals for ANOVA with response (Figure 22) appeared to have a significant departure from the normal quantiles, and when looked at the histograms, it was not bell shaped.

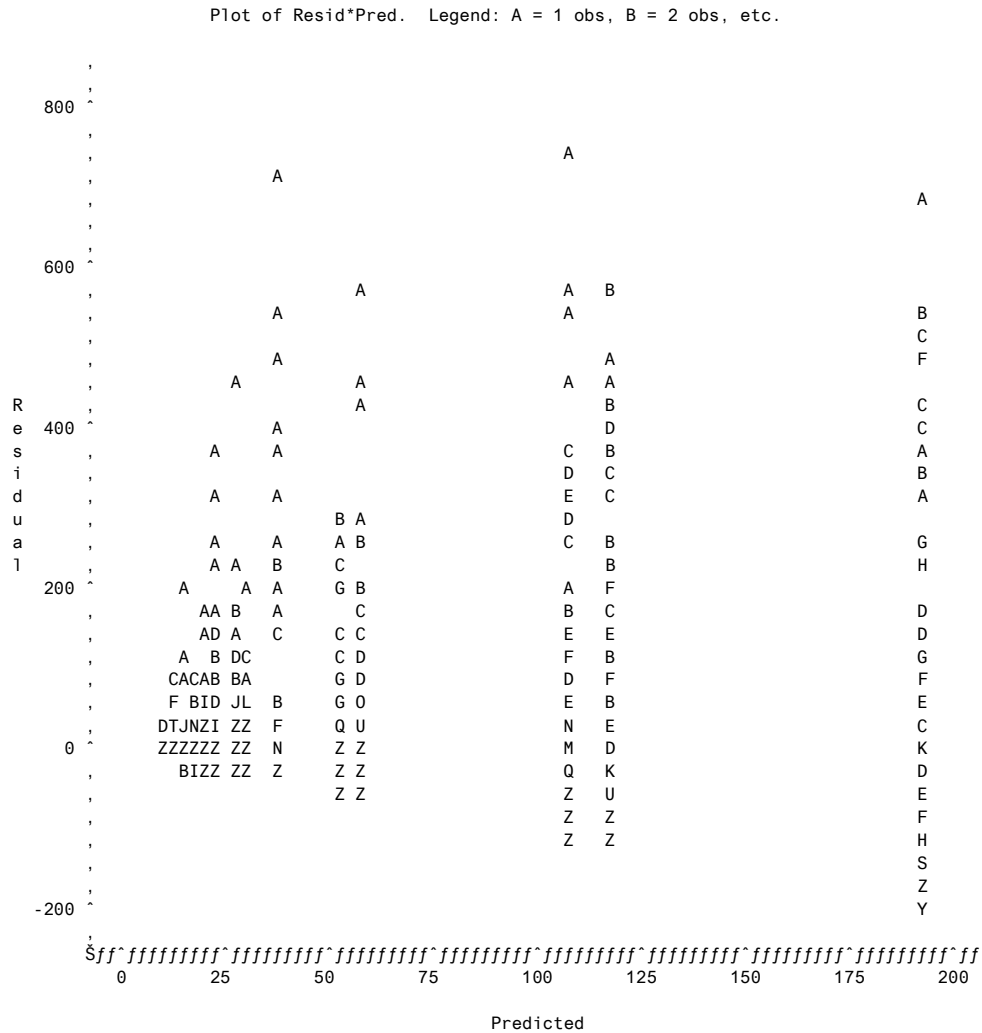


Figure 21: ANOVA w/proc Mixed Normality of residuals test plot of residuals by fitted values before transforming acknowledge time data to Log values

Since the data was not normally distributed, a logarithmic transformation was performed, which produces a residual plot that the violation does not appear to be significant. Figure 23 and 24's transformed data seems to indicate that the homogeneity of variance and normality assumptions are no longer violated.

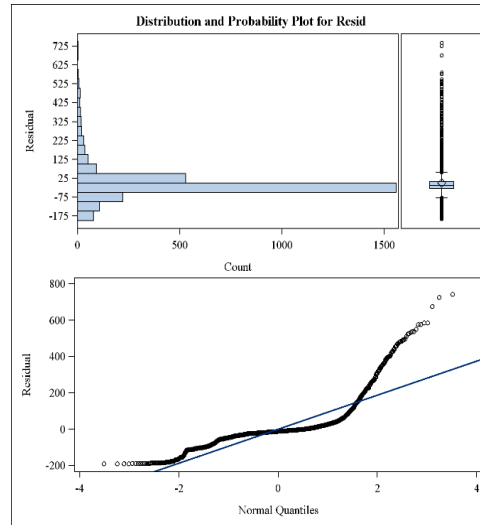


Figure 22: Residuals for ANOVA with response

#### Hypothesis 2 Analysis:

Table 12 provides information on different interactions between display types, alarm types, and alarm rates. The interaction of display types and alarm rates was significant ( $F = 54.65$ ,  $p\text{-value} = 0.0001$ ). Following the same, it can be said that the interaction between display types and alarm types is also statistically significant ( $F = 5.24$ ,  $p\text{-value} = 0.0003$ ). Interaction across alarm rates and alarm types is also statistically significant ( $F = 23.47$ ,  $p\text{-value} = 0.0001$ ). So, it can be concluded that acknowledge time has statistically significant effect on different interactions between display types, alarm rates, and alarm types.

Table 12: Factorial ANOVA Proc-Mixed output for all main effects and interactions (\*  $P \leq 0.05$ )

Effect	Num DF	Den DF	F Value	Pr > F
Display	2	2772	90.94	<.0001 *
Rate	1	2772	121.52	<.0001 *
Type	2	2772	4.14	0.0160 *
Display*Rate	2	2772	54.65	<.0001 *
Display*Type	4	2772	5.24	0.0003 *
Rate*Type	2	2772	23.47	<.0001 *
Display*Rate*Type	4	2772	0.60	0.6615

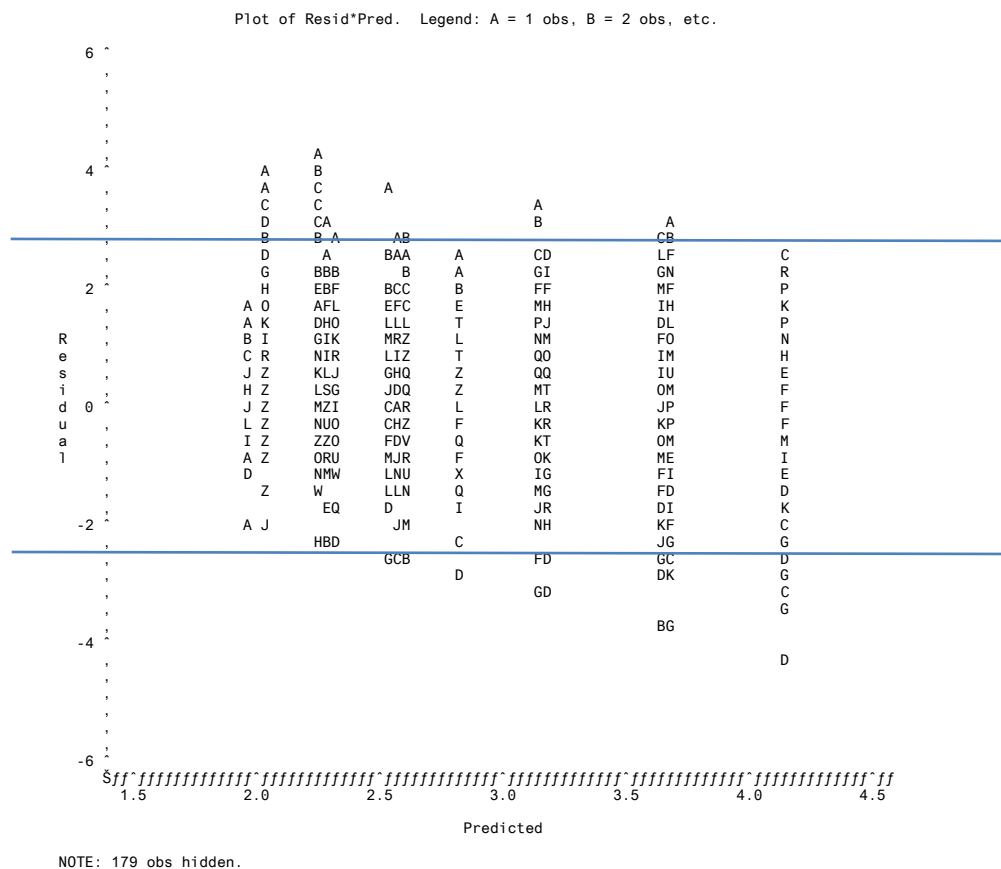


Figure 23: ANOVA w/proc Mixed Normality of residuals test plot of residuals by fitted values after transforming acknowledge time data to Log values

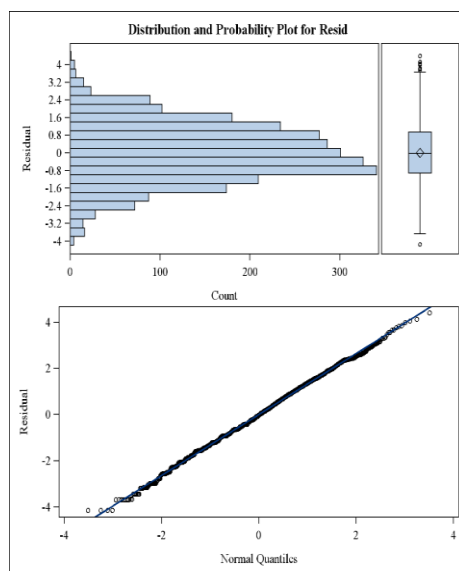


Figure 24: Residuals for ANOVA with log response



For each significant interaction, the LS Means (Least Square Means) Tukey-Kramer means test was performed to determine which group performed the best. Tukey-Kramer method was performed to find which groups were different from one another. Different letter groupings help to understand if differences between two groups are statistically significant.

#### Display Type and Alarm Rate Interaction Analysis

Table 13 shows the interaction across display types and alarm rate depending upon the participants' acknowledge time. It helps to compare between displays depending on the alarm rates. Response time for different alarm rates have differences, and it is statistically significant as the letter grouping is different.

The overall performance of participants for 10 alarms in 10 minutes were better than the overall performance of participants for 20 alarms in 10 minutes. But there is a common letter grouping, which is 'C', can be seen among different display types for alarm rate of 10 alarms in 10 minutes, which projects that the differences among different display types for alarm rate of 10 alarms in 10 minutes are not statistically significant.

Significant differences can be found in case of alarm rate of 20 alarms in 10 minutes, as the letter groupings are for chronological, categorical, and revised categorical displays are different and they are 'A', 'B', and 'D' respectively. Participants performed best for the display type revised categorical, as the estimate value is 2.0993 which is the lowest among all displays for the alarm rate of 20 alarms in 10 minutes.

So, participants' performed better on revised categorical display for alarm rate 20 in 10 minutes than for alarm rate 10 in 10 minutes on both categorical and chronological displays. It is an interesting finding and helps to understand that alarm display can make an impact on human performance.

Table 13: Interaction between Display Type and Alarm Rate

Display	Rate	Estimate	LS Mean in Seconds	Letter Group
Chronological	20	3.6618	38.93	A
Categorical	20	3.2274	25.21	B
Chronological	10	2.5050	12.24	C
Categorical	10	2.3747	10.75	C
Revised Categorical	10	2.2873	9.85	CD
Revised Categorical	20	2.0993	8.16	D

#### Display Type and Alarm Type Interaction Analysis

Table 14 shows the interactions across display types and alarm types depending upon the participants' acknowledge time. Estimate values can help to compare interfaces depending on alarm types, which are high-1, medium-2, and low-3. It can also be concluded if those differences are statistically significant from the letter groupings.

Table 14: Interaction between Display Type and Alarm Type

Display	Alarm Type (high-1/medium-2/low-3)	Estimate	LS Mean in Seconds	Letter Group
Chronological	1	3.2384	25.49	A
Chronological	2	3.1492	23.32	AB
Categorical	1	2.9810	19.70	AB
Chronological	3	2.8626	17.51	ABC
Categorical	2	2.8510	17.31	BC
Categorical	3	2.5712	13.08	CD
Revised Categorical	3	2.3269	10.25	DE
Revised Categorical	2	2.1452	8.54	E
Revised Categorical	1	2.1078	8.23	E

In case of high-1 priority alarms, statistically significant difference does not exist between display types chronological and categorical but a statistically significant difference exists for the interface type revised categorical. As the letter grouping of chronological type is 'A' and letter grouping of categorical type is 'AB', both have a common letter which is 'A', so, they cannot be predicted as statistically significantly different. But the estimate value of categorical type (2.9810) is lower than the estimate value of chronological type (3.2384), so, it can be concluded that participants responded well for categorical type interface but not statistically significantly. The estimate value of revised categorical type (2.1078) is the lowest and has letter grouping as 'E', so, it can be concluded that participants performed best on revised categorical display for high-1 priority alarm type and it is statistically significant.

In case of medium-2 priority alarms, the letter groupings for interface types chronological, categorical, and revised categorical are 'AB', 'BC' and 'E' respectively. So, it can be concluded that the difference between chronological display and categorical display is not statistically significant. The difference between chronological display and revised categorical display, as well as the difference between categorical display and revised categorical display are statistically significant. From the estimate values of three different display types, it is found that the revised categorical display has the lowest value, which is 2.1452. So, it can be concluded that participants performed best on revised categorical display for the medium-2 type alarms.

In case of low-3 priority alarms, the letter groupings for interface types chronological, categorical, and revised categorical are 'ABC', 'CD' and 'DE' respectively. So, it can be concluded that the difference between chronological display and revised categorical display is statistically significant. The difference between chronological display and categorical display is not statistically significant. And the difference between categorical display and revised

categorical display is also not statistically significant. Among the estimate values of three different display types, it is found that the revised categorical display has the lowest value, which is 2.3269. So, it can be concluded that participants performed best on revised categorical display for the low-3 type alarms.

Participants' performance on chronological display had no significant difference between all alarm types, and the performance were worst among all three different alarm displays. Interestingly, participants' performance on revised categorical alarm display among all alarm types had no significant difference but they were the best comparing between all display types. Though revised categorical display for low alarm type was not significantly different from categorical display for low alarm type, the estimate value was better than both categorical (for high, medium, and low alarm types) and chronological (for high, medium, and low alarm types) displays. Hence, this finding supports the notion that alarm display can impact and improve the human performance. In case of critical alarms or high level alarm type, participants' performed best on the revised categorical display.

#### Alarm Rate and Alarm Type Interaction Analysis

Table 15 shows the interaction between alarm rates and alarm types. High priority alarm - 1 is statistically significantly different, as it has a letter grouping 'A', which is different among all interactions. From the estimate values it can be concluded that participants performed better for alarm rate of 10. It is also noticeable that for low priority alarm – 3, participants have performed better than both high priority alarms – 1 and medium priority alarms – 2, where alarm rate 20 is considered.

Table 15: Interaction between Alarm Rate and Alarm Type

Rate	Alarm Type (high-1/medium-2/low-3)	Estimate	LS Mean in Seconds	Letter Group
20	1	3.3490	28.47	A
20	2	2.9619	19.33	B
20	3	2.6776	14.55	C
10	3	2.4962	12.14	CD
10	2	2.4684	11.80	CD
10	1	2.2024	9.05	D

### Hypothesis 3

Null Hypothesis  $H_0$  : No difference exist in participant accuracy of response given different alarm interface types.

Alternate Hypothesis  $H_1$  :  $H_0$  is false.

Dependent Variable: Accuracy of Response

Independent Variable: Interface types (Chronological, Categorical, and Revised Categorical)

GLIMMIX (General Linear Mix models) was used as the testing method to analyze the third hypothesis. For a dataset, normality of residuals and homogeneity of variance are two assumptions to be made to perform simple ANOVA test. But the mentioned assumptions are not required when performing generalized mix models (GLIMMIX) test. This experimental method generates binary numbers as the accuracy of response dataset, and binary values don't have any normal distribution, so, GLIMMIX procedure was used.

During performing the GLIMMIX test, a blocked test was performed by blocking the alarm rate, and alarm type, because only concern is the accuracy of each task, that participants performed for different display types, and not for the alarm rate and alarm type.

Table 16 shows that the main effect display is statistically significant ( $F = 8.78$ ,  $p\text{-value} = 0.0002$ ).

Table 16: GMIMMIX test output for the Main effect Display (\*  $P \leq 0.05$ )

Type III tests of fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Display	2	2782	8.78	0.0002 *

Table 17 shows that the difference between chronological and categorical display is not statistically significant, as both have the letter grouping as 'A', but the difference with revised categorical display is statistically significant, as it has a different letter grouping, as 'B'. From the estimate value it can be concluded that participants performed most accurately for revised categorical display type, as it has the lowest value.

Table 17: Interaction between Interface Types

Display (Chronological/Categorical/Revised Categorical)	Estimate	Mean	Letter Group
Chronological	-3.0639	0.04462	A
Categorical	-3.2255	0.03822	A
Revised Categorical	-4.5381	0.01058	B

The similar test had been performed by blocking display type and alarm rate. From the Table 18, it can be understood that the main effect alarm type is statistically significant ( $F = 6.11$ ,  $p\text{-value} = 0.0023$ ).

Table 18: GLIMMIX test output for the Main effect Alarm Types (\*  $P \leq 0.05$ )

Type III tests of fixed effects				
Effect	Num DF	Den DF	F Value	Pr > F
Type	2	2782	6.11	0.0023 *

Table 19 shows that the difference between high level alarm and medium level alarm is not statistically significant, as both have the letter grouping as ‘B’, but the difference with low level alarm is statistically significant, as it has a different letter group, as ‘A’. From the estimate value it can be concluded that participants performed most accurately for medium level alarm - 2, as it has the lowest value.

Table 19: Interaction between Alarm Types

Type	Estimate	Mean	Letter Group
3	-3.0694	0.04439	A
1	-3.7546	0.02287	B
2	-3.9198	0.01946	B

Subjective usability test:

After the completion of the experiments operators were given a questionnaire to know their perspective and feelings about the simulation and different interfaces. They expressed different views on different alarm interfaces and the overall simulation system, and results are shown as a column chart in Appendix 11. From the feedback it could be understood that majority of the participants were satisfied with the information provided to understand the tasks. The alarm messages were clear to understand easily, and 54.83% participants voted “strongly agree”. 67.74% participants agreed that the organization techniques used for the system were very clear and easy to understand. 83.87% participants thought that they could adapt the system quickly and be productive. Overall the participants were satisfied with the system including pipeline window, pumping stations, alarm management display. Feedback was taken from each operator about the preferred alarm display. The feedback shows that among 31 participants 24 students (78%) accepted the revised categorical interface as the best, 6 students (19%) chose the categorical

interface over the other two, and only one student (3%) preferred the chronological interface. From the pie-chart (Figure 16) we can see an exponential increase in participants' preferences.



## **CHAPTER 5: DISCUSSION & 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 is focused on alarm display and the interface design aspects.

From the above analysis and discussion, participants performed best on revised categorical display. The primary goal of the alarm management display is to notify control room operator about the critical or abnormal situation. Different abnormal situations are prioritized as high (1- critical), medium (2 - medium), and low (3 - low) alarms. During this experiment participants were clearly instructed to work on high alarm first, following the medium level and low level alarms. Table 10 and 14 that display how alarm types were handled only on the revised categorical display where participants were able to handle alarms in order of priority (highest to lowest). But in the case of the chronological display and categorical display the behavior was erratic, and does not follow the prioritization levels. This seems to indicate that the revised categorical display provided some feature that ultimately affected operator performance. During the experiment as alarms piled up, participants had to search for alarms. In chronological display the visual search was most difficult, as there was no categorical list, and participants had difficulties finding newer high-level alarms within the stack of alarms containing all types of alarms. The categorical display groups alarms by priority so it seems to reduce visual search; however, since the list is always changing where the alarm being handled is in the list changes location thus increasing users search time. The revised categorical display, while similar to the

categorical display, displays the latest alarm at the top of the list of each alarm type. After acknowledgement it disappears from the list and appears in a separate list of acknowledged alarms. As a result the stack of unacknowledged alarms shrinks which reduces visual search as participants had to search among lower number of alarms if they had a stack of unacknowledged alarms. Alarm appearing at the top of the list reduced response time and acknowledgement time as users could easily skim through between different alarm type lists and find the latest alarm.

Macdonald (1999) talked about the use of colors in effective graphics, and using of colors in showing alarms. Aarlien (2004) suggested magenta color as the low level alarm color. Stanton and Stammer (1998) gave importance on prioritization and organization of alarms. So, various researchers have discussed elements that could improve alarm management systems. Different prioritization and organization techniques for alarms had been used in this study to build different alarm management displays. There were mainly two different alarm displays (chronological and categorical) following the prioritization techniques of chronology based and category based. There was another alarm management display (revised categorical) where a different organization technique was followed while maintaining the acknowledged alarms. Different color combinations for different alarms are also used across three different displays. So, this study followed many recognized and suggested techniques of building alarm management display, but there was no previous study which can be related with this study, as, this is an unique study where different alarm prioritization and organization techniques had been used together.

Uhack's (2010) research explored the effect of different alarm rates on controller response and found that performance decreased significantly when users were faced with the alarm rate of 20 alarms in 10 minutes. As this study is an extension of the mentioned research,

only the different alarm rates of 10 alarms in 10 minutes and 20 alarms in 10 minutes were used. Buddaraju's (2011) experiment on the performance of control room operators on categorical and chronological displays found that control room operators were more productive on categorical alarm management display. This study supports the previous findings. This study included two different type of categorical displays, and results showed a significant participants' performance difference between two different categorical displays (categorical display and revised categorical display). Thus this series of experiments has found that human performance is both affected by the alarm rates (e.g., 20 per 10 minutes) and the display type. Different organization techniques of alarms shows that controller response can be improved through better displays than the traditional chronological display.

As this experiment is in-lab experiment, it has many constraints but it has been understood from the analysis that there definitely has an impact of color coding on alarm management interface, as different colored alarm management interfaces were used, and there certainly has an impact of different type of alarm listing management. Though participants liked the revised categorical alarm interface the most, but they also expressed that sometimes they wanted to re-check the alarm which had already been acknowledged, but in revised categorical display, acknowledged alarms go to a separate acknowledged alarms list, and the color stays the same, that is why they had to struggle a little. So, it might be a good research area to change colors on acknowledged alarms and making separate list for acknowledged alarms, then find their impact. It is said that people do not detect color change well in peripheral vision, but movement such as flashing, is readily detected. Alarms thus readily stand out on a graphic and are detectable at a glance (Hollifield, 2012). There might be a good research of using sound notification for alarms and find its impact.

The experiment was taken place in a controlled lab environment of Louisiana State University and the participants were all undergraduate students. So, the tasks were simpler than the real world and not tested with real world operators, so, there are many factors left untouched from human factors point of view, which need further attention and could be considered as future research. The areas of focus would include the following:

- The project was experimented on Louisiana State University undergraduate students and not on real-time operators, so, further studies on real-time operators might help to find better notions on alarm management system. And the project can be extended by increasing the complexity of both the simulation and alarms, as there can be more complex alarm conditions in real world.
- A further study can be done using different variables like different times of a day and night, lighting condition (bright light, dim light) of control room, background noise (like people humming, chatting, song is being played). Effect of nuisance alarms on operators needs further attention and could be done by increasing the nuisance alarm numbers in a given time. Stress level of operators and evaluating the impact of it on operator performance, by developing longer time experiments could be a useful future study.
- A further study of Alarm window color management might give a better notion of using proper foreground and background colors depending on relative luminance. Impact of primary colors and secondary colors in alarm management system should need more attention and a further study could be done on effect of colors at different time of the day and night, and also at different stress levels. Different types of categorical display could play a significant role too, so, including different displays like keeping acknowledged

alarms at its initial position versus a separate list of acknowledged alarms versus keeping acknowledged alarms at its initial position but just changing color.

## REFERENCES

- Aarlien, Ragnar, and Skourup, Charlotte. 2004. "Cool, calm and collected: No cause for alarm on the Grane oil rig", ABB Review Report, Doc No. 9AKK100580A0947. Vol. 19, No. 4.
- American Petroleum Institute (API). (2007). API - RP 1165: Recommended Practice for Pipeline SCADA Displays. API Publishing Services 1220 L Street, N.W., Washington, D.C. 20005, United States.
- American Petroleum Institute (API). 2008. API – RP 1168: Recommended Practice for Pipeline Control Room Management.
- American Petroleum Institute (API). 2009. API – RP 1167: Recommended Practice for Pipeline Control Room Alarm Management.
- Buddaraju, Dileep. 2011, "Performance of Control Room Operators in Alarm Management". The Department of Engineering Science, Louisiana State University.
- Butikofer, R. E. 1986. "Safety Digest of Lessons Learned", API Publications 758. American Petroleum Institute, Washington DC.
- Chang, James I. and Lin, Cheng-Chung. 2006, "A Study of storage tank accidents", Journal of Loss Prevention in the Process Industries, Vol. 19, Issue 1, January 2006, Pages 51-59.
- Crichton, M and Flin, R. 2001. "Training for emergency management: tactical decision games". *Journal of Hazardous Materials*, Volume 88, Issues 2-3.
- "Dead of Night: Fatigue culprit in major accidents". 2008. *Occupational Health Management*. Vol. 18 Issue 9, p102.
- Easterby, R. and Zwaga, H. 1984. "Tasks, processes and display design, in Easterby." *Information Design*, Chichester: Wiley, 19-36.
- EEMUA (1999). Alarm systems: a guide to design management and procurement. London, Engineering Equipment and Materials Users Association.
- Errington, J., Reising, D. V. and Harris, K. 2006. "ASM outperforms traditional interface." *Chemical Processing*, 69(3): 55-58.
- Hachiya, Y., Ogai, H., Okazaki, H., Fujisaki, T., Uchida, K., Oda, S., Wada, F. and Mori, K. 2010 "Methods of Collection of Biological Information for Fatigue Evaluation during Visual Display Terminals (VDTs) Operation." *Electronics and Communication in Japan*, Vol. 93, No. 9.

- Hassan, M. F. Abu, Yusof, Y., Azmi, M. A. and Mazli, M. N. 2012. "Fuzzy Logic Based Intelligent Control of RGB Color Classification System for Undergraduate Artificial Intelligence Laboratory". *Proceedings of the World Congress on Engineering* Vol. II.
- Hollifield, Bill (PAS Principal Consultant), PAS. 2012. "A High Performance HMI: Better Graphics for Operations Effectiveness".
- Hollifield, Bill and Habibi, Eddie of PAS, foreword by Ian Nimmo. 2006. "The Alarm Management Handbook: A Comprehensive Guide".
- Hollifield, Bill R. and Habibi, Eddie. 2007. "Alarm Management: Seven Effective Methods for Optimum Performance". *Instrumentation, Systems, and Automation Society (ISA)*. ISBN-13: 978-1-934394-00-7; ISBN-10: 1-934394-00-9.
- Hollifield, Bill R. and Habibi, Eddie. 2010. "The Alarm Management Handbook". Second Edition, ISBN: 978-0-9778969-3-6.
- Hori, S. and Shimizu, Y. 1999. "Designing methods of human interface for supervisory control systems". *Control Engineering Practice* 7(11): 1413-1419.
- ISA (2008). ISA – 18.2 – (2008). Management of Alarm Systems for the process Industries. ISA – Instrumentation, Systems, and Automation Society, Research Triangle Park, NC 27709, United States.
- Lysaght, Robert J., Hill, Susan G., Dick, A. O., Plamondon, Brian D, Linton, Paul M., Wierwille, Walter W., Zaklad, Allen L., Bittner, Alvah C. Jr. and Wherry, Robert J. 1989. "Operator Workload: Comprehensive Review and Evaluation of Operator Workload Methodologies." Technical Report 851.
- MacDonald, W. Lindsay. 1999. "Using Color Effectively in Computer Graphics." IEEE Computer Graphics and Applications (Impact Factor: 1.23), 0272-1716/99. DOI: 10.1109/38. 773961. Issue 2/2004.
- Moe, Christine L. and Rheingans, Richard D. 2006. "Global Challenges in Water, Sanitation and health". *Journal of Water and Health*. IWA publishing. Color Matters. (2011, March). "How the Eyes Sees Color"[online].
- Nimmo, I. 1995. Abnormal situation management, New Orleans, LA, USA, Instrument Society of America, Research Triangle Park, NC, USA.
- Nimmo, I. 2002. "It's time to consider human factors in alarm management." *Chemical Engineering Progress* 98(11): 30-38.
- Nimmo, I. 2011. Alarm Management and Graphics Projects. Retrieved March 10, 2011, from <http://mycontrolroom.com>;

[http://mycontrolroom.com/site/component/option,com\\_docman/task,cat\\_view/gid,16/Itemid,24](http://mycontrolroom.com/site/component/option,com_docman/task,cat_view/gid,16/Itemid,24).

- Ormsbee, Lindell E. and Lansey, Kevin E. 1994. "Optimal Control of Water Supply Pumping Systems". *Journal of Water Resource Planning and Management*. Vol 120, No. 2: 237-252.
- Pate-Cornell, M. Elisabeth. 1985. "Fire Risks in Oil Refineries: Economic Analysis of Camera Monitoring". *Society for Risk Analysis*, Vol.5, No.4.
- Pipeline and Hazardous Materials Safety Administration (PHMSA), D. O. T. (2008). Pipeline Safety: Control Room Management/Human Factors; Proposed Rule. Federal Register/Vol. 73. No. 178. 49 CFR Parts 192, 193, and 195.
- Pourbeik, Pouyan, Kundur, Prabha S. and Taylor, Carson W. 2006. "The Anatomy of a Power Grid Blackout". *IEEE publishing* September/October 2006, Power and Energy magazine.
- Preece, Jenny, Rogers, Yvonne and Sharp, Helen. March 23, 2007. "Interaction Design: beyond human-computer interaction". Wiley, John and Sons, Inc.
- Rasmussen, B. 1989. "Chemical Process Hazard Identification." *Reliability Engineering and System Safety* 24(1): 11-20.
- Sanders, Mark S. and McCormick, Ernest J. 1993. "Human Factors in Engineering and Design". 7<sup>th</sup> Edition, McGraw-Hill, Inc.
- Special Investigation Division, Committee on Government Reform, U.S. House of Representatives. 1999. "Oil Refineries Fail to Report Millions of Pounds of Harmful Emissions".
- Stanton, N. A. and Stammers, R. B. 1998. "Alarm initiated activities: Matching formats to tasks." Lawrence Erlbaum Associates. *International Journal of Cognitive Ergonomics*. 2(4) 331-348.
- Swaen, G. M. H., Amelsvoort, L. G. P. M. van, Bultmann, U., and Kant, I. J. 2002. "Fatigue as a risk factor for being injured in an occupational accident: results from the Maastricht Cohort Study". *Occup Environ Med* 2003, 60: i88-i92.
- Tverdohleb, Igor, Vizenkov, Grigory, and Biryukov, Alexander. 2012. "Oil Pipeline from Siberia to The Sea". *World Pumps*, Volume 2012, Issue 6, May 2012, Pages 26-27.
- U.S. Department of Transportation, Pipeline and Hazardous Materials, Safety Administration, Fatigue Mitigation Panel. 2010.



Uhack, Glen II. 2010, "Empirically evaluating and developing alarm rate standards for liquid pipeline control room operators." The Department of Construction Management and Industrial Engineering, Louisiana State University.

## **APPENDIX 1: DEMOGRAPHIC SURVEY**

1. Name
2. Age
3. Gender
4. Major
5. GPA
6. Computer skill rating: Ex. 1 being not accustomed at all through 5 being a programmer
7. How often do you play computer games?
8. Have you ever used any simulation software before?

## APPENDIX 2: QUIZ QUESTIONNAIRE

Participant's Name: \_\_\_\_\_, Age: \_\_\_\_\_, Dept.: \_\_\_\_\_

### General Knowledge Quiz:



This symbol means the pump is open. True / False.



This symbol means the pump is closed. True / False.



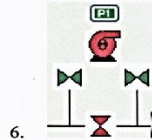
This symbol means the valve is open. True / False.



This symbol means the valve is closed. True / False.



This symbol means the valve is malfunctioning. True / False.



This condition is called 'power trip'. True / False.

7. How do you handle the 'power trip' condition?

- Left click on the small green colored button above the pump.
- Right click on the red colored pump and left click on 'START'.



Clicking on this small green colored button would do what?

- Shut down the pump, nothing will happen to any valve.
- Only valves will be closed, nothing will happen to the pump.
- Shut down the entire pumping system (*i.e.* pump, suction valve, discharge valve) and open the Bypass valve.

9. If in any pumping station leak happens, how do you understand exactly where it has happened?

- Left click on each device and look for certain pressure drop.
- Left click on each device and look at the flow rate.

### APPENDIX 3: SUBJECTIVE 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**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

4. It was simple to use this system.

**STRONGLY  
AGREE**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

7. I felt comfortable using this system.

**STRONGLY  
AGREE**  
**COMMENTS:**

**1      2      3      4      5**

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

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

**STRONGLY  
AGREE**  
**COMMENTS:**

1 2 3 4 5

**STRONGLY  
DISAGREE**

15. I liked using the interface of this system.

**STRONGLY  
AGREE**

1 2 3 4 5

**STRONGLY  
DISAGREE**

**COMMENTS:**

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

**STRONGLY  
AGREE**

**1**

**2**

**3**

**4**

**5**

**STRONGLY  
DISAGREE**

**COMMENTS:**

17. Overall, I am satisfied with this system.

**STRONGLY  
AGREE**

**1**

**2**

**3**

**4**

**5**

**STRONGLY  
DISAGREE**

**COMMENTS:**

## APPENDIX 4: EEMUA NO. 191 BENCHMARK AVERAGE ALARM RATE STANDARD

Long Term Average Alarm Rate in Steady Operation	Acceptability
>1 alarm per minute	Very likely to be unacceptable
1 alarm per two minute	Likely to be excessively demanding
1 alarm per five minutes	Manageable
<1 alarm per ten minutes	Very likely to be acceptable

## APPENDIX 5: ISA 18.2 AVERAGE ALARM RATE STANDARDS

Very Likely to be acceptable	Maximum Manageable
~150 Alarms per day	~300 Alarms per day
~6 Alarms per hour (average)	~12 Alarms per hour (average)
~1 Alarm per 10 minutes (average)	~2 Alarms per 10 minutes (average)



## APPENDIX 6: TABLE IDENTIFYING MEANING OF COLORS

Page 526 of (MPR Associates and Laboratory 2004), table on meaning of colors.

Color	Typical Meaning
<b>Red</b>	<ul style="list-style-type: none"> <li>• Fire protection equipment and apparatus</li> <li>• Danger</li> <li>• Stop or trip (for a control)</li> <li>• Running or “ON”</li> <li>• Valve open</li> <li>• Breaker closed</li> <li>• Alarm of High Priority</li> <li>• Abnormal condition</li> </ul>
<b>Orange</b>	<ul style="list-style-type: none"> <li>• Dangerous parts of machinery or equipment, such as open breaker boxes</li> <li>• Alarms of Intermediate priority</li> </ul>
<b>Yellow</b>	<ul style="list-style-type: none"> <li>• Physical hazards, such as falling or tripping</li> <li>• Caution</li> <li>• Alarm of Intermediate priority</li> <li>• Abnormal condition</li> <li>• In manual mode</li> <li>• In standby</li> <li>• Not in desired post ESFAS Initiation status</li> </ul>
<b>Green</b>	<ul style="list-style-type: none"> <li>• Personnel health or safety</li> <li>• Location of first aid equipment</li> <li>• Not running or “OFF”</li> <li>• Valve closed</li> <li>• Breaker open</li> <li>• Normal condition</li> <li>• Alarm cleared</li> </ul>
<b>Blue</b>	<ul style="list-style-type: none"> <li>• Caution against starting, using or moving equipment in use</li> <li>• Bypassed</li> <li>• In standby</li> <li>• Selected</li> <li>• Normal condition</li> <li>• In desired post ESFAS Initiation state</li> <li>• Water</li> <li>• Secondary water</li> <li>• Primary water (cyan)</li> </ul>
<b>Magenta</b>	<ul style="list-style-type: none"> <li>• Radiation hazards (used in combination with yellow)</li> <li>• Abnormal condition</li> </ul>
<b>Black and/or White</b>	<ul style="list-style-type: none"> <li>• Traffic and housekeeping markings</li> <li>• Status indications</li> <li>• Neutral information</li> <li>• In automatic mode</li> <li>• A non-priority alarm</li> <li>• Text</li> <li>• Steam (gray)</li> </ul>

## APPENDIX 7: PARTICIPANTS REJECTION AND SELECTION CHART

Participant No.	Quiz Score (9 possible)	Video Games	Computer Skill (scale of 1 to 5)	Hydraulic Software use	Rejected/Selected	Successful completion of experiment
Pilot	9	Sometimes	3	No	Selected	Yes
Pilot	9	Never	3	No	Selected	Yes
Pilot	8	Sometimes	3	No	Selected	Yes
Pilot	7	Never	3	No	Selected	Yes
Pilot	9	Sometimes	4	No	Selected	Yes
1	7	Never	3	No	Selected	Yes
2	8	Never	3	No	Selected	Yes
3	9	Sometimes	4	No	Selected	Yes
4	8	Never	4	No	Selected	Yes
5	9	Never	3	No	Selected	Yes
6	9	Never	3	No	Selected	Yes
7	9	Sometimes	4	No	Selected	Yes
8	9	Sometimes	3	No	Selected	Yes
9	9	Sometimes	3	No	Selected	Yes
10	9	Sometimes	3	No	Selected	Yes
11	8	Sometimes	3	No	Selected	Yes
12	9	Sometimes	3	No	Selected	Yes
13	9	Sometimes	4	No	Selected	Yes
14	9	Sometimes	4	No	Selected	Yes
15	9	Sometimes	3	No	Selected	Yes
16	9	Sometimes	3	No	Selected	Yes
17	9	Never	3	No	Selected	Yes
18	9	Sometimes	3	No	Selected	Yes
19	9	Sometimes	3	No	Selected	Yes
20	9	Sometimes	4	No	Selected	Yes
21	8	Sometimes	3	No	Selected	Yes
22	9	Never	3	No	Selected	Yes
23	9	Sometimes	3	No	Selected	Yes
24	9	Sometimes	3	No	Selected	Yes
25	9	Sometimes	3	No	Selected	Yes
26	9	Sometimes	3	No	Selected	Yes
27	9	Sometimes	3	No	Selected	Yes
28	9	Sometimes	3	No	Selected	Yes
29	9	Sometimes	3	No	Selected	Yes
30	9	Sometimes	3	No	Selected	Yes
31	9	Sometimes	3	No	Selected	Yes
32	9	Sometimes	3	No	Selected	Failed
33	8	Sometimes	4	No	Selected	Failed
34	9	Never	3	No	Selected	Failed
35	9	Never	3	Yes	Rejected	NA
36	6	Never	2	No	Rejected	NA
37	9	Extensive	5	No	Rejected	NA

## APPENDIX 8: LIST OF 10 ALARMS PRESENTED IN 10 MINUTE SESSION

Alarm	Description
1	Station 6, Pump 15, "POWER TRIP"
2	Station 2, Pump 6, "BYPASS VALVE MALFUNCTION"
3	Leak at station 1
4	Station 4, Pump 11, "HIGH DISCHARGE PRESSURE"
5	Leak between Station 4 and Station 6
6	Station 2, Pump 5, "LOW SUCTION PRESSURE"
7	Station 3, Pump 8, "LOW FLOW RATE"
8	Leak at Station 2
9	Station 8, "BLOCK VALVE 24 MALFUNCTION"
10	Leak at Station 3

## APPENDIX 9: LIST OF 20 ALARMS PRESENTED IN 10 MINUTE SESSION

Alarm	Description
1	Leak at Station 5
2	Station 7, Pump 18, "BYPASS VALVE MALFUNCTION"
3	Station 1, Pump 1, "POWER TRIP"
4	Station 4, Block valve 15, "PRESSURE SENSOR FAILURE"
5	Leak between Station 1 and Station 3
6	Leak at Station 7
7	Station 7, Block valve 21, "FLOW SENSOR TIMEOUT"
8	Station 3, Pump 8, "LOW SUCTION PRESSURE"
9	Leak at Station 3
10	Station 6, Pump 16, "BYPASS VALVE MALFUNCTION"
11	Station 8, Pump 20, "HIGH DISCHARGE PRESSURE"
12	Leak at Station 2
13	Station 3, Pump 8, "POWER TRIP"
14	Station 2, Block valve 11, "BYPASS VALVE MALFUNCTION"
15	Station 1, Pump 2, "BYPASS VALVE MALFUNCTION"
16	Station 2, Pump 5, "LOW SUCTION PRESSURE"
17	Leak at Station 2, "MAIN DISCHARGE PIPE"
18	Leak at Station 8, "MAIN DISCHARGE PIPE"
19	Station 4, Main Discharge Pipe, "LOW FLOW RATE"
20	Station 4, Pump 10, "POWER TRIP"

## APPENDIX 10: IRB APPROVAL FORM

### Application for Exemption from Institutional Oversight

Unless qualified as meeting the specific criteria for exemption from Institutional Review Board (IRB) oversight, ALL LSU research/projects using living humans as subjects, or samples or data obtained from humans, directly or indirectly, with or without their consent, must be approved or exempted in advance by the LSU IRB. This Form helps the PI determine if a project may be exempted, and is used to request an exemption.



Institutional Review Board  
Dr. Robert Mathews, Chair  
203 B-1 David Boyd Hall  
Baton Rouge, LA 70803  
P: 225.578.8692  
F: 225.578.6792  
irb@lsu.edu | lsu.edu/irb

- Applicant, Please fill out the application in its entirety and include the completed application as well as parts A-E, listed below, when submitting to the IRB. Once the application is completed, please submit two copies of the completed application to the IRB Office or to a member of the Human Subjects Screening Committee. Members of this committee can be found at <http://www.lsu.edu/irb/screeningmembers.shtml>
- A Complete Application Includes All of the Following:
  - (A) Two copies of this completed form and two copies of parts B thru E.
  - (B) A brief project description (adequate to evaluate risks to subjects and to explain your responses to Parts 1 & 2)
  - (C) Copies of all instruments to be used.
    - If this proposal is part of a grant proposal, include a copy of the proposal and all recruitment material.
  - (D) The consent form that you will use in the study (see part 3 for more information.)
  - (E) Certificate of Completion of Human Subjects Protection Training for all personnel involved in the project, including students who are involved with testing or handling data, unless already on file with the IRB.  
Training link: (<http://cme.cancer.gov/clinicaltrials/learning/humanparticipant-protections.asp>.)

1) Principal Investigator: Craig M. Harvey, Ph.D., P.E. Rank: Assistant Professor Student? Y/N

Dept.: Industrial Eng. Ph: 225-578-8761 E-mail: harvey@lsu.edu

2) Co Investigator(s): please include department, rank and e-mail for each

If student, please identify and name supervising professor in this space

Glen Uhack II (Master's Student)

guhack1@tigers.lsu.edu

Supervising professor - Craig M. Harvey

3) Project Title: Developing Alarm Management Guidelines for SCADA Operations

4) LSU Proposal? (yes or no) Yes If Yes, LSU Proposal Number 35226

Also, if YES, either ☒ This application completely matches the scope of work in the grant OR ☐ More IRB Applications will be filed later

5) Subject pool (e.g. Psychology Students) Eng. students and SCADA Operators

• Circle any "vulnerable populations" to be used: (children <18; the mentally impaired, pregnant women, the aged, etc.) None Projects with incarcerated persons cannot be exempted.

6) PI Signature [Signature] \*\* Date 7/29/09 (no per signatures)

"I certify my responses are accurate and complete. If the project scope or design is later changed I will resubmit for review. I will obtain written approval from the Authorized Representative of all non-LSU institutions in which the study is conducted. I also understand that it is my responsibility to maintain copies of all consent forms at LSU for three years after completion of the study. If I leave LSU before that time the consent forms should be preserved in the Departmental Office."

\*\*\*Effective August 1, 2007, all Exemptions will expire three years from date of approval, unless a continuation report, found on our website, is filed prior to expiration date\*\*\*

Screening Committee Action: Exempted ☒ Not Exempted ☐ Category/Paragraph 2

Reviewer Mathews Signature [Signature] Date 8/6/09

Study Exempted By: Dr. Robert C. Mathews, Chairman  
Institutional Review Board  
Louisiana State University  
203 B-1 David Boyd Hall  
225-578-8692 | [www.lsu.edu/irb](http://www.lsu.edu/irb)  
Exemption Expires: 8/2/2012

IRB# 4465 LSU Proposal# 35226  
☒ Complete Application  
☒ Human Subjects Training

## Consent form for Alarm Management 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](mailto:irb@lsu.edu), [www.lsu.edu/irb](http://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: \_\_\_\_\_

**Study Exempted By:**  
Dr. Robert C. Mathews, Chairman  
Institutional Review Board  
Louisiana State University  
203 B-1 David Boyd Hall  
225-578-8692 | [www.lsu.edu/irb](http://www.lsu.edu/irb)  
Exemption Expires: 8-5-2012

## APPENDIX 11: CONSENT FORM

Title:

Effect of Different alarm interfaces on controller response.

Work Site:

The experiments will be conducted at LSU laboratory to study effect of different interfaces types on control operators (e.g., category vs. chronological alarm management system).

Contacts:

1. Craig M. Harvey, Ph.D., P.E.  
Interim Chair, Associate Professor  
Dept. of Construction Mgt & Industrial Eng  
3128 Patrick F. Taylor Hal  
Louisiana State University  
Baton Rouge, LA 70803  
Ph: 225-578-8761 (M-F 9am-4pm)  
Email: [harvey@lsu.edu](mailto:harvey@lsu.edu)
2. Aritra Datta  
Masters in Engineering Science (student)  
Louisiana State University  
Ph. 225-270-6163 (M-F 9am-4pm)  
Email: [adatta3@lsu.edu](mailto:adatta3@lsu.edu)

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](mailto:irb@lsu.edu), and [www.lsu.edu/irb](http://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.'

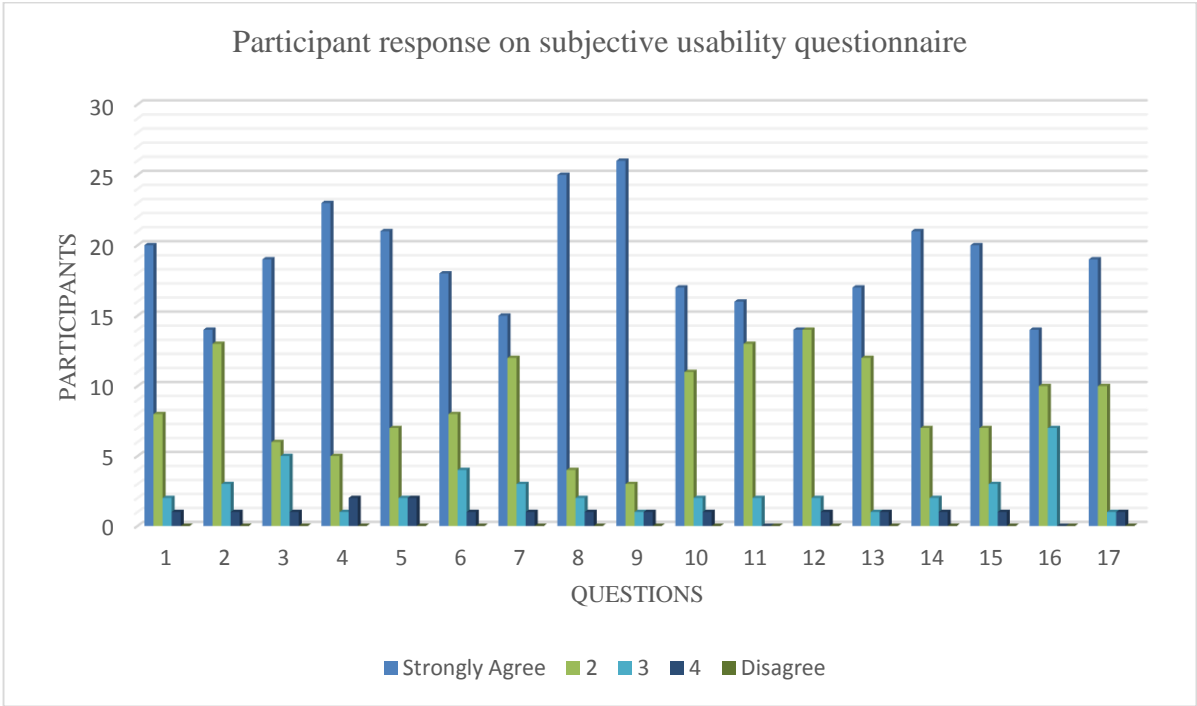
Subject Signature:\_\_\_\_\_ Date:\_\_\_\_\_

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 12: SUBJECTIVE USABILITY QUESTIONNAIRE RESULT**



## APPENDIX 13: PARTICIPANTS' MEAN ACKNOWLEDGE TIME AND MEAN RESPONSE TIME

		Mean (Acknowledge Time)		
		Chronological	Categorical	Revised Categorical
10 - 10 Mins.	High	35.87	36.05	9
	Medium	65.35	55.24	16
	Low	68.03	52.63	21
20 - 10 Mins.	High	379.43	241.72	38
	Medium	180.34	104.24	21
	Low	136.18	75.68	13

Mean values of Participants' Acknowledge Time (in Seconds) for different Interface Types, Alarm Types and Alarm Rates

		Mean (Response Time)		
		Chronological	Categorical	Revised Categorical
10 - 10 Mins.	High	18.35	19.18	14.68
	Medium	37.87	27.91	25.23
	Low	42.23	32.13	34.44
20 - 10 Mins.	High	192.27	130.91	82.92
	Medium	74.63	52.81	32.86
	Low	80.18	47.45	41.97

Mean values of Participants' Response Time (in Seconds) for different Interface Types, Alarm Types and Alarm Rates

Acknowledge Time	
Alarm Type	Mean (Seconds)
1 – High	89.97
2 – Medium	46.79
3 – Low	29.41

Mean values of Participants' Acknowledge Time for different Alarm Types

Response Time	
Alarm Type	Mean (Seconds)
1 – High	105.41
2 – Medium	44.96
3 – Low	49.01

Mean values of Participants' Response Time for different Alarm Types

## APPENDIX 14: SAS CODE FOR RESPONSE TIME OR ACTION TIME ANALYSIS

```
ods rtf file = 'F:\Alarm\Alarm1.rtf';
```

```
libname Sas "F:\Alarm";
```

```
data clock;  
set Sas.Alarm8;  
lresponse=log(response);  
run;
```

```
proc mixed data=clock;  
class display rate type;  
model lresponse=display Rate type display*rate display*type rate*type display*rate*type /  
ddfm=satterth outp=outdata ;  
lsmeans display Rate type display*rate display*type rate*type display*rate*type / adjust=tukey  
pdiff;  
ods output diffs=ppp1 lsmeans=mmm1;  
run;  
%include 'F:\Alarm\pdmix800.sas';  
%pdmix800(ppp1,mmm1,alpha=0.05,sort=yes);  
RUN;
```

```
proc univariate data=outdata NORMAL PLOT;  
var resid;  
run;
```

```
ods rtf close;
```

## APPENDIX 15: SAS CODE FOR ACKNOWLEDGE TIME ANALYSIS

```
ods rtf file = 'C:\Consulting\Project2\logAcknoledge.rtf';

libname Sas "C:\Consulting\Project2";
data alarm;
set Sas.Acknowledge1;
lack=log(acknowledge);
run;

proc mixed data=alarm;
class display rate type;
model lack=display Rate type display*rate display*type rate*type display*rate*type /
outp=outdata ;
lsmeans display Rate type display*rate display*type rate*type display*rate*type / adjust=tukey
pdiff;
ods output diffs=ppp1 lsmeans=mmm1;
run;
%include 'C:\Consulting\pdmix800.sas';
%pdmix800(ppp1,mmm1,alpha=0.05,sort=yes);
RUN;

proc univariate data=outdata NORMAL PLOT;
var resid;
run;

proc plot data=outdata;
plot resid*pred;
run;

ods rtf close;
```

## APPENDIX 16: SAS CODE FOR ACCURACY OF RESPONSE ANALYSIS

```
ods rtf file = 'C:\Consulting\Project2\Accuracydisplay.rtf';
```

```
libname Sas "C:\Consulting\Project2";
```

```
data alarm3;
```

```
set Sas.Accuracy;
```

```
run;
```

```
proc glimmix data=alarm3;
```

```
class display rate type;
```

```
model Accuracy= display / dist=binary ;
```

```
random type rate rate*type;
```

```
output out=output pred=p resid=r;
```

```
lsmeans display / adjust=tukey pdiff ilink;
```

```
ods output diffs=ppp1 lsmeans=mmm1;
```

```
run;
```

```
%include 'C:\Consulting\pdmix800.sas';
```

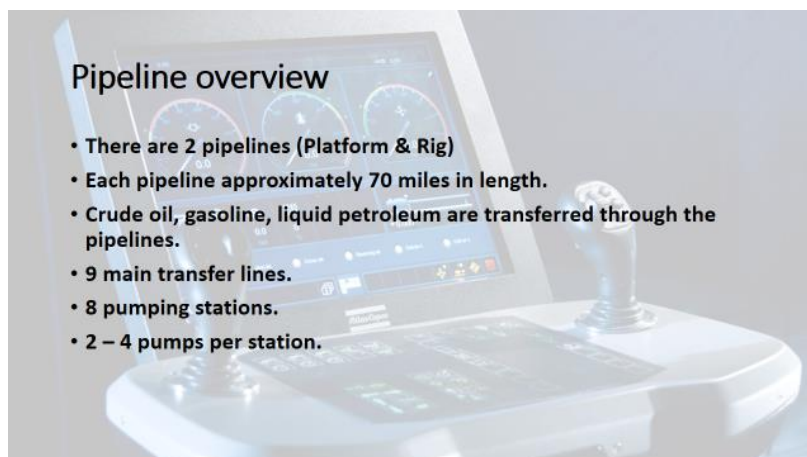
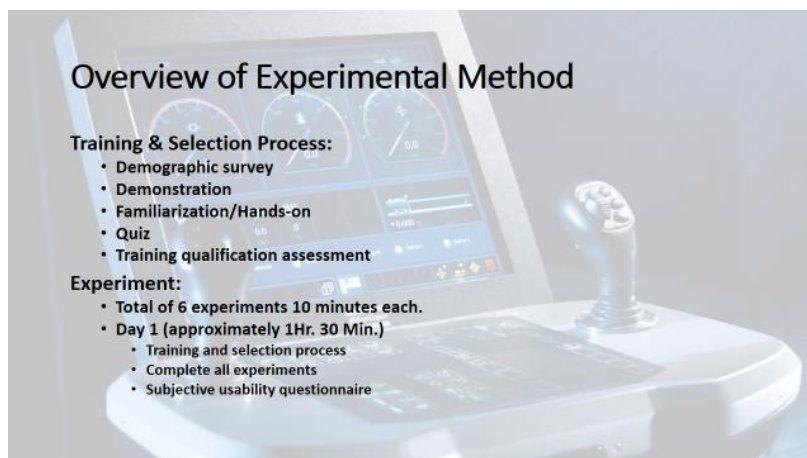
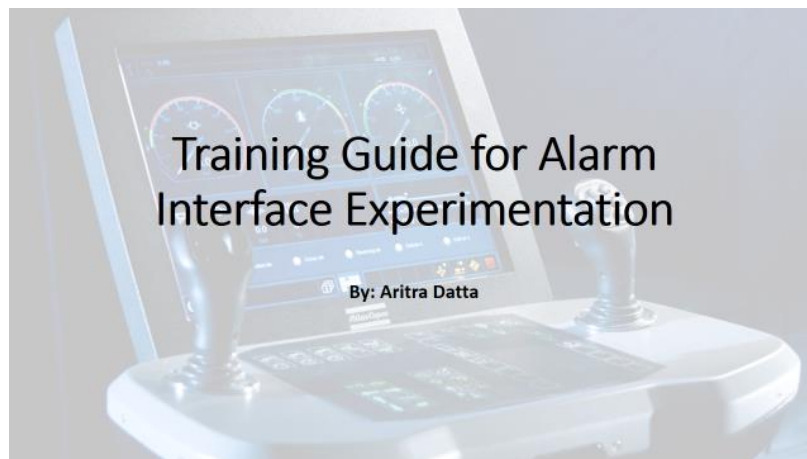
```
%pdmix800(ppp1,mmm1,alpha=0.05,sort=yes);
```

```
RUN;
```

```
run;
```

```
ods rtf close;
```

## APPENDIX 17: POWER-POINT PRESENTATION FOR TRAINING



## Key attributes:

- Pipeline system can face any abnormal situation during the liquid transportation, and it includes the following:
  - Leak events
  - Power failures
  - Equipment malfunctions
  - Equipment failures
- Operator will be notified of any abnormal situation by an alarm, and it has three priority levels as follows:
  - Red – high priority alarms
  - Yellow – Caution or medium priority alarms
  - White or Magenta – low priority alarms

## Standard operating procedure

Different actions should be taken while handling different alarmed conditions, as follows:

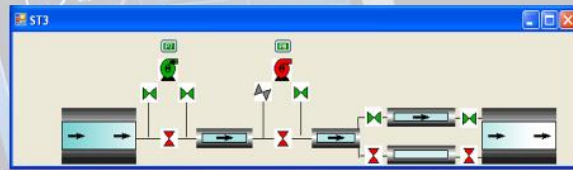
- Leaks
  - Identify origin or flow leaving the pipeline.
  - Two steps should be followed. Shutdown sequence for a specific pump should be initiated followed by rerouting flow through Bypass station discharge pipes.
  - Shutdown or blocking an entire station increases abnormality and crashes at the end.
- Pump trip or Power interruption
  - Simply restart the pump.
- Equipment malfunction
  - Returning equipment to normal operating mode.
- Submit a maintenance request for any non-repairable or hardware fix.

## Overview Simulation System Display





## Detailed Station Display



## Graphical Representation



Questions ?

## **THE VITA**

Aritra Datta was born in Kolkata, West Bengal (India), in 1984. He received a bachelor's degree in Electronics and Communication Engineering at the Institute of Technology and Marine Engineering under West Bengal University of Technology, West Bengal in May 2006. He works as a research assistant during his time as a master's student in the Department of Mechanical and Industrial Engineering.