Human Factors and Ergonomics in Offshore Drilling and Production: The Implications for Drilling Safety

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The primary mission of the OESI is to provide a forum for dialogue, shared learning, and cooperative research among academia, government, industry, and other non-governmental organizations, in offshore energy-related technologies and activities that ensure safer and environmentally responsible offshore operations. The OESI strives to coordinate and focus efforts to identify scientific and technological gaps and to recommend improvements of drilling and production equipment, practices, and regulation. OESI also gathers, considers, and harmonizes the proposals promoted by other research and development centers and other groups to inform BSEE on technological and other developments within the offshore industry. Additionally, the OESI provides a forum for the continuous education and training of BSEE and BOEM employees to ensure that the federal workforce maintains the same level of technological expertise as the engineers, scientists and technical experts in the oil and gas industry.

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INTRODUCTION

There are approximately 4,000 drilling platforms located in the Gulf of Mexico and when incidents occur on offshore platforms, the results can be catastrophic. The consequences can be environmental, economic, and of course, in case of injury and loss of life, personal and tragic. A recent example of this is the Deepwater Horizon explosion on the Macondo well (Macondo), where 11 were killed and the gushing well resulted in the largest oil spill in the US history that has cost BP $59 billion in court fees, penalties, and cleanup costs, not to mention loss of revenue (Graham et al., 2011). Further, the environmental impact of the estimated 184 million-gallon spill is still being assessed, and the economic costs to the Gulf coast community have been profound. The lives lost of course are the most poignant cost of this incident as these losses cannot be recovered and they ripple through the closely-knit community of the offshore drilling workers' families.

In response to this incident, the industry and the government have reflected on methods for preventing incidents ensuring safe and environmentally responsible offshore operations. Given the complexity of offshore drilling, this is a non-trivial goal and will require a multifaceted, multidisciplinary approach. One effort, suggested by the National Academy of Science's Committee on Offshore Oil and Gas Safety Culture in their 2015 report, was to create organization whose goals are to facilitate the development and exchange of knowledge among and between academia, government, industry, and other non-governmental organizations. This led to the development of the Ocean Energy Safety Institute (OESI: oesi.tamu.edu). Further efforts, given that some failures that result in incidents such as Macondo are associated with technology such as the Blow Out Preventer (BOP) not operating as expected during the event and the associated problems with the cement used for the well (Graham et al., 2011), have focused on preventing another major blow out and spill in the Gulf of Mexico through technological solutions and mitigations.

While these efforts are well placed, they will likely not be sufficient unless they are designed in a manner that considers the humans that use or touch this technology during the development lifecycle of the technology. Indeed, often a disaster is attributed to "human error," and there has been discussion about the human error associated with Macondo. One of us has asked the question, in the literature, "But which human?," (Bias & Gillian, 1997). That is, was the error the fault of the human worker, or of the designer who placed in front of that worker a design or system that made it difficult for the worker to identify and interrupt the problem? This is the realm of human factors.

Organizations differ in their definitions of Human Factors, but it is formally defined by the Human Factors and Ergonomics Society in the following manner:

> *Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and other methods to design in order to optimize human well-being and overall system performance (hfes.org).*

Thus, the idea is to understand how the human interacts with the elements of the system and then apply that understanding to design in order to make the system safer and more effective. Some of these applications can be domain agnostic, as the way the human interacts with certain systems does not differ by domain. For instance, we know that the visual contrast between text and background influences readability. Presenting yellow text on a white background will have a negative impact on performance, whether the display is on an oil rig, a car dashboard, or an office workspace. However in some domains, the elements and complexities of the system can be

unique and thus require specific systematic investigations and applications of the interactions between the human and the system to facilitate effective design. Some industries have been integrating human factors (HF) principles, methodologies, and content for many years. For instance, the military has been leveraging HF in the design of their equipment since World War II (Chapanis, Garner, & Morgan, 1949) and in their training protocols since the late 20th century (Salas, Prince, Baker, & Shrestha, 1995). After the incident at Three Mile Island, the nuclear industry formally required human factors principles and processes in the design of their systems and control panels (Endsley & Garland, 2000).

For those HF academics and practitioners who have addressed HF for the offshore oil and gas industry (O&G), and particularly offshore O&G in the Gulf of Mexico, the consensus is that the consideration and application of human factors principles and practices lags dangerously behind that in the military, nuclear, and other industries. However, this "consensus" may be regional based in the United States, as there has been extensive European interest in Ergonomics (in Europe, the terms Ergonomics and Human Factors are synonymous) and O&G particularly since the Piper Alpha incident in 1988 where 167 people were killed and regulations associated with HF and Ergonomics (HF/E) were enacted (Broadribb, 2015; Gordon, 1998). Indeed in response to Piper Alpha, in 1998 Gordon provided an outline of how HF/E could be related to and predict human error in the offshore environment. Further, in the spring of 2016, COMAH Competent Authority (UK's regulatory agency) published the HF Delivery Guide that "supports the Competent Authority's (CA) programme of regulating major hazards, by establishing a clear framework to inspect human factors (HF) at COMAH establishments" (Human Factors Delivery Guide, 2016, p. 2). The HF Delivery Guide clearly and explicitly communicates to the O&G community the need to integrate HF design and operational principles and all stages of the operations in order to mitigate hazards.

There has been some work toward integrating HF into O&G in the Gulf of Mexico by contractors and agencies (Miller, 1999; Planners, 2007; Robertson, 1999; Thomas et al., 2002). However, there has not been a systematic or widespread integration of these methodologies into the construction, deployment, operation, and shut in of the O&G rigs outside the UK. An interesting side note to this is a position paper written by Sonneman in 1992 that clearly articulates attributes of behaviorism, perception, attention, bias, culture, and training that can explain why drillers sometimes delay in responding to kick. Although HF is not mentioned in this paper and Mr. Sonneman has no human factors training, this is what he is describing and what he is advocating the industry address to improve well control and prevent blow outs (Sonneman, 1992). Clearly there has been knowledge of HF and how it can help prevent these incidents for quite some time. The challenge now is to determine how much knowledge there is, how scientifically sound that knowledge is, and to determine why it has not been incorporated fully into this industry.

This paper will present a summary of the current literature on the status of the O&G industry with regard to the adoption and integration of HF methods, principles, and processes. There are two primary reasons for this secondary research (literature review) on the current OESI research area of human factors. The first is to ensure that the OESI takes full advantage of all the existing best practices, and helps drive, among member organizations, empirically-based excellence in the pursuit of drilling safety. That is, what does the industry know right now, what information do we have about user interface (UI) design, about individual human performance, about social interactions and communication flow, about work flow, about management practices—information that would, if integrated into drilling design and practices, minimize the chances of injury or disaster and maximize production up time?

The second reason for such a literature review is to identify gaps in our research, or perhaps

better, next areas that deserve our attention as human factors researchers, to improve substantially our collective wisdom about safe drilling practices.

It is our belief that this information will illuminate potential systematic risks that are and are not being addressed and will steer our industry toward what can be done to reduce the likelihood of incidents occurring offshore—in the oil and gas industry in general and in the Gulf of Mexico specifically.

METHODS
Search for Primary Data
The literature search began with a Google Scholar database search using terms generated by combining the keywords *human factors* or *ergonomics* and *offshore* with all of the following: *drilling*, *production*, *fatigue*, *situation awareness, cognitive, oil and gas,* as well as a search for *human error offshore.* Second, we supplemented the first search with a similar search of the Web of Science database using only *human factors offshore* and *ergonomics offshore* search terms. Next, we supplemented our search of primary studies in the published literature with a search of papers and abstracts within conferences, including Research Partnership to Secure Energy for America (RPSEA), Offshore Technology Conference (OTC), Mary Kay O'Connor Process Safety Center (MKOPSC), International Association for Drilling Contractors (IADC), Offshore Oil and Gas Producers (OOGP), Society for Petroleum Geophysicists (SPG), American Institute for Chemical Engineers (AIChE), Center for Offshore Safety (COS), and Center for Operator Performance (COP). This search was included, as many contractors in O&G will publish papers in these venues that do not get indexed with primary study publications.

These efforts resulted in an initial list of 112 papers. A number of different inclusion/exclusion strategies were used to refine these results. Because our focus was on human factors work in offshore environments, studies focusing on onshore facilities were automatically excluded and unrelated domain applications like medicine, software development, and energy policy were also excluded. Further, with the topics identified, more specific literature searches were conducted after the original search that added papers to each category. After the exclusion criteria were applied and additional papers were added, 191 papers were identified across all categories, and some of these papers were used in more than one category.

A NOTE ABOUT OUR DATA SEARCH: While we are confident in the approach we took to find resources, we are also humble about our ability to exhaustively sample the research findings that are "out there". If some members of the OESI are aware of any related findings (perhaps once-proprietary, but no longer), we would welcome pointers thereto.

Categorizing data
Each of the papers was reviewed for the topics covered in the paper and overall the papers contained 13 distinct topics associated with HF/E. The papers were coded to identify which of the 13 topics were addressed in the paper (as many addressed multiple topics). The topics are listed in Table 1 and are specifically: Crew Resource Management; Design & Installation; Fatigue; Human-Machine Interaction; HF/E Standards & Regulations; Interface Design; Overview of HF/E in O&G; Quantitative Risk Analysis; Risk Perception; Safety Culture/Climate; Situation Awareness; Stress. Further, through the forums held by OESI and through expert review, three additional HF/E topics being explored in the offshore O&G environment were identified—specifically, Alarm Management, Automation, and Procedures. The papers were grouped according to their topics and summaries of the current state of the knowledge regarding these topics are presented here. During the summarization of the groupings, searches for additional

references were conducted on the specific topics (*e.g.*, fatigue and situation awareness) to ensure that the current literature on the topic had been sufficiently reviewed. The exclusion criteria for these references of only being related to the offshore environment was removed for these references as some were used to explain and illustrate other applications of the constructs. Further, some of the original references were deemed not necessary to include in the summaries, as they were either redundant or not sufficiently related to offshore O&G. Our topics are listed in Table 1, in alphabetical order, along with counts of the number of articles our searches unearthed. In the next section we offer the results of our investigation, that is, a summary of research in each of these topics.

Table 1. Listing of paper topics and number of papers for each topic

Topic	Original	Removed	Added	Final
Alarm Management	-	-	7	7
Automation	-	-	9	9
Crew Resource Management	7	3	9	13
Design & Installation	15	2	-	13
Fatigue	4	-	6	10
Human-Machine Interaction	1		9	10
HF/E Standards & Regulations	10	3	8	15
Interface Design	-	-	13	13
Overview of HF/E in O&G	8	2	7	13
Procedures	-	-	9	9
Quantitative Risk Analysis	28	7	13	34
Risk Perception	3	-	1	4
Safety Culture/Climate	16	6	1	11
Situation Awareness	9	3	5	11
Stress	11	2	10	19
Total	112	28	107	191

RESULTS
The summaries of existing research regarding HF/E are presented below with a summary of the current state of the science. Rather than addressing these topics in alphabetical order, as they are presented in Table 1, here we present them in a more meaningful order. So, we start with topics associated with design (Design & Installation; HFE Standards & Regulations; Interface Design), then move into operations, addressing individual performance (Procedures; Risk Perception; Fatigue; Stress; Situation Awareness; Alarm Management; Automation) and conclude with team performance (Safety Climate/Culture; Quantitative Risk Analysis). Note that those references in the Overview of HF/E in O&G are primarily in the Introduction. For each topic we discuss current gaps in the science and literature and address needed topics for future research.

EXISTING RESEARCH

1. DESIGN AND INSTALLATION
While Human Factors and Ergonomics (HF/E) is the scientific discipline of integrating the work of the human into systems and machine interfaces, Human Factors (HF) engineering can be considered the practice of actually applying the science of HF/E and is the most relevant during

the design and installation of offshore facilities. Miller defined HF engineering with regard to the O&G industry as a discipline aimed at addressing the integration of the human with the system during different phases of design, construction, decommissioning *etc.* through application of practical activities (OGP, 2011; Robb & Miller, 2012). There have been efforts to integrate and implement aspects of HF engineering in offshore O&E design from incorporating cultural issues (McCafferty, Hendrikse, & Miller, 2004) to designing emergency escape and other safety efforts (Kjellén, 2007; Lewis & Griffin, 1997; Skogdalen, Khorsandi, & Vinnem, 2012) and here we will describe those efforts primarily associated with the installations of new facilities (Robertson, 1999).

The harsh environment of the Arctic requires application of HF engineering, where maintenance is a critical issue for operation in O&G installations. Kumar *et al.* provides a guideline on how to implement HF/E principles to reduce risks and improve maintainability of the offshore O&G industry (Kumar, Barabady, Markeset, & Kumar, 2009). The guideline focuses on incorporating ergonomic features in design and facility layout that will aid in maintainability, such as designing to provide visual, anthropomorphic and physical access to workers and task simplification.

Walker *et al.* emphasized the importance of tackling the ergonomics issues associated with the control rooms in offshore installations (Walker, Waterfield, & Thompson, 2014). They conducted a survey covering a third of all North Sea oil production and identified HF/E issues around control room operation, *e.g*., the alarm overflow, use of control room for non-control room operation, difficulties associated with emergency situations. There are additional guidelines featuring ergonomics of control room design. For example, one study presented some guidelines based on the interventions of six offshore control rooms (Souza da Conceição, Duarte, Maia, & Cordeiro, 2010). Some of the guidelines generated from the study included removal of non-essential personnel from the control room, separating control room from the equipment and operation to avoid noise, designing control room to ensure interaction between workers, designing rest room and other facilities to a suitable vicinity of the control room.

McSweeney & McCafferty represented HF engineering as a key element in Human System Integration (HSI) performance objectives (McSweeney & McCafferty, 2006). They describe all the elements of HSI, including manpower, personnel training, HF engineering, system safety, health hazards, habitability, and survivability. Their Human Factors Engineering Implementation Program (HFEIP) is a process designed to facilitate the implementation of HSI and specifically involves the development of the HFEIP plan that should be developed and implemented by both the owner and contractor of offshore oil and production units. McSweeney *et al.* identified 14 tasks as part of the HFEIP task plan that include but are not limited to review and development of design document, identifying HFE task, conducting training, special audits, and performing Computer Aided Design (CAD) reviews (McSweeney, de Koker, & Miller, 2008; McSweeney & McCafferty, 2006). Through the HFEIP, the owner and contractors declare clear objectives, establish project timelines, and provide instruction as specific as which contractor to select. Through HFEIP implementations the developers of HFEIP have learned that there needs to be commitment from management side for implementation, effective HF engineering planning, and early involvement of HFE in the project plan. In fact, the sooner HF engineering is integrated into the lifecycle of a design, the more cost-effective the project becomes (McSweeney et al., 2008).

Some case studies of successful implementation of HFE into O&G revealed the economic viability of application of HFE (BMT Designers & Planners, 2007). For one of the projects on the Mars offshore platform, HFE specialists identified problems with the turbine and worked with the vendor to redesign it. Before redesigning the work area, the turbine needed to be dismantled from the top and sides and there were significant hazards associated with the dismantling. With the

new design, maintenance personnel worked from the sides and internal monorails were used rather than cranes, and this was a safer and more efficient procedure. The new design reduced the maintenance time from 10 to 3.5 hours. This reduction in time for maintenance hours can easily be translated into Return On Investment calculations for this specific project. Similar case studies revealed how an effective HFEIP can have a positive and cost-effective impact on the safety and performance of offshore installation (BMT Designers & Planners, 2007).

Gaps:
Benefits of using HF in design and installation—both in cost, time, and safety—need to be shared across the industry: Although the methods described here have been used to some degree, there is a general lack of sharing of these successes and validations of their benefits over time. These benefits have significant safety implications and thus the industry leaders need to determine methods and contents that can be shared amongst industry partners to benefit all. Kumar *et al.* provides a guideline on how to implement HF/E principles to reduce risks and improve maintainability of the offshore O&G industry (Kumar et al., 2009). However, the study identified gaps in considering only issues like cost, material, and equipment characteristics *etc.* to be a part of continuous research and did not validate their findings.

Further development of the frameworks need to be conducted to insure complete coverage and integration of the rig functioning and allow for effective ROI calculation: Currently there are few, if any, frameworks that can integrate human-centered design concepts throughout the rig design process and can identify crucial elements specific to design stages. There are also gaps in establishing examples of successful implementation and identification of the Key Performance Indicators (KPI) and Return of Investment (ROI) for all of the methods presented. Some of them mention being able to (*e.g.,* BMT Designers & Planners, 2007), but this was not the focus of their efforts.

2. HUMAN FACTORS/ERGONOMICS (HF/E) STANDARDS AND REGULATIONS.
Standards and regulations are developed and provided as a method of communicating the minimum standards by which a company must operate to be effective and safe. There are multitudes of standards available across the world for many different industries and disciplines. Effectively navigating and implementing these documents for any company is non-trivial at best. Incidents in the Gulf of Mexico and around the world have emphasized the safety risks and highlighted the significance of human factors and their associated standards for safe operations in O&G (Albrechtsen & Besnard, 2014). Over the past two decades, ergonomic factors within the design of machinery, facilities, and work activities have been methodically considered for a small number of the offshore facilities. These considerations are focused on occupational risks of personnel, supporting operations and maintenance, and improving the wellbeing of their workers (Hendrikse et al., 2002). Several regulatory bodies and industry associations such as the UK's Health and Safety Executive (HSE), the American Society of Testing and Materials (ASTM), Oil and Gas Producers (OGP), and Norway's Petroleum Safety Authority (PSA) have developed regulations, standards, and/or guidelines focusing on the application HFE principles in the development and operations of O&G projects (ABS, 2012, 2014b; Hendrikse et al., 2002; HSE, 2002; Robb & Miller, 2012).

Despite the development of these standards and their validation for improving workers' safety and efficiency, HF/E integration into the design of these facilities has been inhibited by the lack of understanding and inconsistent implementation across projects (Johansen, 2014; HSE, 2002). One of the main reasons noted for this has been a general misunderstanding of HF/E by engineers (possibly associated with this training not being required in many curriculum guidelines) and

inadequate HF/E expertise and guidance for specific applications of design practices and principles into the design projects for offshore (ABS, 2014b; Robb & Miller, 2012). For example, the American Petroleum Institute (API) recently mandated Recommended Practice 75 (API, 2004) which incorporates directives that Human Factors should be considered, but gives no specific guidance on the appropriate steps or directions for implementation. Another reason for the lack of HF/E integration could be that without the proper management participation and buy-in, the integration of HF/E concepts and knowledge are not be applied effectively (Johansen, 2014). In recent years there has been only a slight increase in guidance from industry-specific HF/E expert personnel. The increase has been based on practical, and project-specific design experiences and its continuation could play a substantial role in improving safety and risks involved in facility design and installation (Robb & Miller, 2012).

To ensure the integration of human factors and ergonomics into the offshore O&G, a multi-disciplinary effort which involves human factors experts working in conjunction with members of industry, academia, regulatory organizations, and professional associations could be the key component for establishing and maintaining appropriately accessible and interpretable sources of HF/E standards. With multiple experts across disciplines sharing information, the collaboration could lead to the development of mitigation strategies for future incidents (Albrechtsen & Besnard, 2014). A prime example of this type of effective collaboration can be observed in the recent study conducted in 2014 by the American Bureau of Shipping (ABS) HF engineering team (ABS, 2014b). The ABS HF engineering team worked in conjunction with the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), the American Petroleum Institute (API) Recommended Practice 2L committee, the Helicopter Safety Advisory Conference (HSAC), and the Gas Turbine Propulsion Laboratory at Texas A&M University to examine and identify several flight safety risks pertaining to methane ingestion in helicopters operating offshore (Holloway, 2015).

Objectives for the collaborative HF engineering study started with the analysis of existing requirements, industry best practices, regulations, and standards for offshore helideck design and installation with a focus on the placement of methane vents and other sources of combustible gasses. Other objectives were to determine methane volume concentration parameters and the effects of ingestion, to evaluate monitoring and sensor technology, and to investigate and recommend mitigation strategies. Results from the investigation provided recommendations and corrective actions that could impact safety procedures and regulations which aim to mitigate the potentially fatal flight safety issues plaguing helicopters serving offshore platforms in the Gulf of Mexico operations every day. Additionally, the review of existing and emergent gas detection methodologies provides guidance for selecting a technology that best mitigates the hazard of methane ingestion. Through the multi-disciplinary effort of the safety assessment, the ABS HF engineering group contributed key findings that could have a significant impact on improving the safety and reliability of helicopter operations in the offshore environment (Holloway, 2015).

In O&G, one of the areas in which HF/E issues are being consistently explored has been in the design of control centers. This has been accomplished through the recognition of HFE standards such as ISO 11064 (ISO-11064, 2013) and alarm standards such as EEMUA-191 (EEMUA-191, 1999). However, there has been more emphasis on the physical ergonomics (layout and work environment) than on the perceptual and cognitive aspects of control room design. A case study performed by Aas & Skramstad examined the industrial application of the control center design standard ISO 11064 (Aas & Skramstad, 2010). The primary objective of the research was to document workers' experiences from applying ISO 11064 to control center designs in full-scale industrial projects such as the construction of new offshore installations (oil platforms, FPSOs, *etc.*) and onshore process installations (only where significant modifications were similar).

According to the scope of ISO 11064, it is intended for non-mobile control centers. On the other hand, it states the principles could apply also to mobile control centers such as those on aircraft and ships (ISO-11064-1, 2010). Nevertheless, applications of the standard to mobile units have been occurring throughout the Norwegian petroleum industry. Moreover, the O&G industries in Norway have also turned their focus towards HFE standards and regulations, specifically in work environments such as facilities, ergonomics design, and human-machine interface and information presentation. Other examples are HF guidelines for the use of closed circuit TV, and guidelines for crew resource management (CRM) training (Johansen, 2014).

These examples of the integration of HFE standards and regulations are encouraging, but recent events in the Gulf of Mexico, (*e.g.*, Macondo) suggest that more guidance is needed. However, ensuring that the O&G industry becomes aware of and effectively uses these future (or current) sets of HF/E standards and guidelines has proven to be difficult. Thus, it is vital that all parties involved in the development of standards understand and have easy access to the appropriate set of HFE standards, such as ISO 11064 (ISO-11064, 2013). To increase the usability and usefulness of these standards it will be important to ensure that the standards are easily accessible and interpreted by both HF/E and industry personnel.

The design requirements described above along with other guidelines have started to be used in the design phases and installation of several O&G facilities by specifying that the offshore structure implements at least one of the HF/E standards (Robb & Miller, 2012). However, due to the complexity and length of some HF/E standards and guidelines, this can be difficult in application in some cases. This issue is amplified by the fact that the content within the standards may be irrelevant for specific projects and personnel often lack the expertise to accurately interpret and apply the standards (Johansen, 2014).

Gaps:
Training on how to implement HF/E Standard and Regulations: Major offshore catastrophic incidents, *e.g.*, the Macondo oil spill in the Gulf of Mexico, reaffirm the significant need to address human factors to ensure safe and reliable operations. Furthermore, the reduction of such risks can be best achieved by early consideration of HF engineering principles in design and engineering phases (HSE, 2002). In this regard, HF engineering standards and regulations provide the minimum requirement of what features should be implemented in the design of offshore installations. While regulatory efforts to establish HFE standards and guidelines are growing, designers and engineers involved in O&G are still struggling with the apprehension and implementation of HF engineering principles in their tasks (Robb & Miller, 2012). Thus, the training needs for their capabilities to understand and apply HF/E standards and regulations should continue to be emphasized (Leva, Naghdali, & Alunni, 2015). On the other hand, HF engineering can play as an underlying principle across different disciplines as it helps design equipment, facilities, and systems that fit human capabilities and limitations (Holloway, 2015). Accordingly, successful integration of HF/E into design necessarily entails multidisciplinary efforts among industries, professional societies, academia, and regulatory agencies. Human factors and safety experts in such teams can facilitate exchange of knowledge across different parties and help with the comprehension of the rationale behind designs (and thus the application in novel situations) (Leva et al., 2015).

HF/F Standards and Regulations should be usable: In order to expedite the application of HF/E standards and regulations, any users should be able to easily access existing documents and also promptly be informed of any changes (revisions or additions). In addition, such regulations and guidelines are required to maintain a high level of usability, that is to say, they should be effective in helping users capture what they need and interpret it straightforwardly. More importantly,

however, technical standards often lack design features necessary to incorporate human factors and ergonomic considerations (OGP, 2011). While less complex projects may stress the compliance with existing technical specifications to control HFE issues, more complex ones require input from HFE specialists and sophisticated HFE design analyses and evaluations (OGP, 2011). Furthermore, HF/E standards and regulations should be established in line with current technical standards so that designers do not get confused among different sets of directives (Leva et al., 2015).

Industry needs to understand the benefit of HF/E standards and regulations: Due to the multidisciplinary nature and the lasting impact throughout the system life cycle, the integration of HFE often necessitates management's willingness to participate in this effort and to buy-in regarding recommended guidelines (Robb & Miller, 2012). And the basis for making such decisions can be demonstrated via a practical and cost-effective approach to applying HFE in O&G.

Better methodologies for identifying root causes of incidents: Current methods for incident analysis tend to stop when the investigator has reached something that can be identified as "human error". Those in HF know, and indeed some in O&G are beginning to understand, that human error is not a root cause but instead is very likely indicative of some of other problem (*e.g.,* display design, fatigue, safety culture). Methods for better investigating incidents and understanding and addressing the true causes will help articulate when incidents are due to human performance factors and error prone system designs versus equipment or mechanical problems.

3.   *HUMAN-MACHINE INTERACTION*

When humans perform a task using a machine of any kind, they are engaging in Human-Machine Interaction (HMI). This is true whether that HMI is physically opening and closing a valve or operating a blow out preventer using a touch screen. For industrial facilities as well as other dynamic socio-technical systems (STS), the design of HMI has been identified as a vital component for process safety, quality, and efficiency (Johannsen, 2007). The increasing complexity of the socio-technical systems associated with offshore drilling and production affects the way workers use machines and has led many to adopt automation to remove the human from the process. Although, this can be beneficial, it also impacts the way work is organized and designed and can inadvertently introduce unexpected risks (Flaspöler et al., 2009). Indeed, recent work has found that many of the current automation level tables associated with human performance may not support performance as well as expected, and in fact may be introducing risks (Endsley, in press).

HMI involved in offshore workers are perceived to be error-prone, and combined with the harsh characteristics of the environment could contribute to unpredictable situations that lead to hazardous conditions (Cacciabue, 2004). Good HMI design has been established as an essential factor for facilitating effective and efficient performance as well as ensuring occupational safety and health for the worker (Endsley, 1996). On the other hand, poor HMI design can negatively impact workers' situation awareness and ultimately their performance; thus inadequate HMI design is a major risk factor for offshore O&G (Endsley, 1996).

Machine or technical systems involved in the dynamic and often real-time applications in the offshore environment include automation, decision-support systems, and interface design. For automated processes, machines are able to perform controlling processes more efficiently than humans (Gressgård, Hansen, & Iversen, 2013). Decision-support systems (DSS) are computer-based applications used to bridge the gap between automation and human strengths and can

facilitate optimal decision making to identify problems, determine solutions, and overcome the barriers to good decision making. However, developing effective DSS for highly complex and dynamic domains such as offshore O&G can be a significant challenge. The systems used in offshore O&G are maintained mostly by analyzing real-time data streams measured from the surface and downhole while drilling (Gundersen, Sørmo, Aamodt, & Skalle, 2012). Poor interaction design where the processes controls are not logically organized, the person is not kept aware of the status of the system, and the displays are not intuitive to read, can contribute to operational errors and potential incidents (Thomas et al., 2002).

In offshore operations, there has been too little regard for effective design methodologies and frameworks for HMI. However, there have been several studies outlining the importance of implementing good HMI designs and relative consequences for poor designs in onshore operations facilities. Specifically, these studies have focused on the relationship between HMI and situation awareness, as well as their impact on worker performance. For instance, in a study conducted by Naderpour *et al.* three large-scale process incidents were examined with a focus on technology and situation awareness (Naderpour, Nazir, & Lu, 2015). In all three incidents' analyses there were inadequate HMI designs of the control system, resulting in workers experiencing a loss in situation awareness, which led to explosions at each of the facilities. Moreover, further examination revealed that the primary cause of these incidents was not the workers. The casual factor was the inherent difficulties associated with the complex systems. The engineers, who did not work with individuals working in control centers or in the field, had created these difficulties when designing the systems (Naderpour et al., 2015).

Another study concentrated on the implementation and consequences of human factors in four control centers as it related to safety management (Johnsen & Liu, 2015). Results indicated that there was a lack of focus on HMI designs in supporting situation awareness that led to worker uncertainty and error. This was most apparent in critical situations and the presentation of safety-critical information. Additionally, there were inconsistencies in the HMI designs throughout the different control systems, which also caused confusion in reading measurements within the same control center. In conclusion, Johnsen & Liu identified that not implementing or incorrectly prioritizing the focus on human factors (and thus HMI design) will impact safety (*e.g.*, may lead to operational errors) and eventually lead to costly incidents and/or incidents (Johnsen & Liu, 2015).

Gaps:
More research needed on Human-Machine Interaction Offshore: Based on this literature review, there are only a handful of studies investigating the potential impacts of (or rather, of not) implementing human-machine interaction in complex socio-technical system design and operations. The findings from these studies are indeed quite concerning and strongly suggest that more work is needed to fully understand how automation and human-machine interaction can effectively be integrated to support and not hinder human performance, particularly with respect to process and occupational safety. The result of this research will help in providing a basis for adopting a maximally usable system, be it automated or a hybrid of human-machine activity. The size and complexity of real-world sociotechnical systems can present significant barriers in their design and comprehension. The models resulting from research in this area would yield effective models and simulations should help enable effective system design, deployment, and sustainment of decisions by supporting accurate, shared mental models of system structure and dynamics, taking into account critical social-organizational and technical system components and their interactions. Again, the increasing complexity of the socio-technical systems associated with offshore drilling and production affects the way workers use machines and has led many to adopt automation to remove the human from the process (Johannsen, 2007). There has been too little

research in pursuing a specific understanding of human factors principles, methods, and engineering will improve safety and efficiency in design and operations of these complex sociotechnical systems. Therefore, targeted, future research should be conducted in an attempt to determine the correct path (*e.g.,* through standards and regulations or through design methodologies) to ensure human factors principles are implemented regularly and reliably into these types of systems.

More research needed on HMI design and situation awareness: Poor HMI design can negatively impact workers' situation awareness (SA) and ultimately their performance; thus inadequate HMI design is a major risk factor for offshore O&G (Endsley, 1996). Due to the continued problems surrounding poor HMI design and SA, continued investigates are needed identifying the factors required for implementing proper HMI designs, specifically those associated with improved worker performance and increased SA. Additionally, a framework regarding the inherent difficulties associated with HMI and STS could facilitate a reduction in inconsistencies in the HMI design throughout the different control systems, which in turn can lead to a reduction in workers' uncertainty and improvement in performance (through consistent use of and familiarity with available information). The systems, guidelines and processes to develop this framework would allow the advancement of intuitive decision support systems to enable higher operational performance at lower risk.

Leveraging simulations for HMI research: Another gap in the research deals with a fundamental understanding of how to employ simulations in HF/E research. Laboratory simulations, training simulators, or on-site observation research could assist researchers in determining which human factors principles account for most of the variance in the design of HMI. This can be accomplished by investigating the connection between these factors with the SA of the operators. This would yield a possible ranking system for hierarchically specifying the human factors affecting HMI design based on their impact on occupational and process safety.

4. INTERFACE DESIGN

Any interaction between a human and machine happens at a specific interface. This interface controls the flow of information from the machine to the user (in terms of displays, alarms and warnings, *etc*.) and from the user to the machine (in terms of input or control devices such as keyboards, push buttons, levers, switches, *etc*.) (Flaspöler et al., 2009). An interface design typically involves the development of software and hardware that permits the exchange of information. Specifically, a user interface is where this exchange of information takes place (Gruhn, 2011). User interface are typically, but not limited to, displays of information in a graphic-based visualization (Graphical User Interface or GUI) through a computer display and monitor for industrial process control and monitoring of systems (Flaspöler et al., 2009). Creating an effective interface design allows the human to communicate with the machines to monitor, supervise, and control processes to ensure efficient, effective, and overall safe control of the process by the worker of that process (Ponsa, Vilanova, & Amante, 2010) (Johannsen, 2007). A good interface design presents information in such a way workers can understand the state of a process, while simultaneously communicating and providing feedback to the workers with the purpose of helping their decision making during a given task (Cacciabue, 2004; Nachreiner, Nickel, & Meyer, 2006). If interface designs accurately incorporate human factors methods, then it is more likely that the systems could augment worker workload and ultimately positively influences efficiency, effectiveness, and safety of the system (Nachreiner et al., 2006).

In the offshore O&G environment, many of the current interfaces for daily and emergency tasks have not been specifically designed to facilitate and support human performance. This is despite

the fact that designing these interfaces has been identified as a critical part in the design of O&G facilities both onshore and offshore, particularly those facilities requiring high-reliability and having hazardous conditions (Leva et al., 2015). There is little empirical research concentrating specifically on the effectiveness of interface designs integrated into facilities. However, there have been a few studies, both onshore and offshore, that have used incident analyses and investigative reports identifying causal effects that were related to poor human-system interfaces. In the incident analysis of the Deepwater Horizon blowout, one of the main questions that arose was "why the drilling crew and the mud logger did not react to anomalous data and kick signals for nearly 50 minutes before the explosion?," (Albrechtsen & Besnard, 2014). According to the Chief Counsel's Report, there were several factors contributing to the crew's failure to detect the warning signals such as concurrent operations being performed, inadequate HMIs, and a reduction in crew situation awareness (Counsel, 2011). There have also been a few studies analyzing causality for onshore incidents where poor interface design has been one of the many root causes. One of those studies explored incident analyses where an explosion occurred in 2008, at a methomyl pesticide production facility in Institute, West Virginia, US. The explosion was due to a runaway chemical reaction of a highly flammable solvent. Analysis revealed workers deviated from the written start-up procedures, and bypassed safety-critical devices (CSB, 2011). A new distributed control system (DCS) had significantly changed the interaction between the workers and the multiple DCS display screens that simulated the process flow. The new visual displays (automated icons), along with the modified command entry method (keyboard to mouse) presented a challenge for workers. The system included several new display screens that simulated the process flow (Naderpour et al., 2015). The system and its unit measurements were unfamiliar to the workers preventing adequate SA and proper operating conditions, thus negatively influencing usability and impairing performance (Naderpour, Lu, & Zhang, 2014).

Gaps:
Interface designs utilized on offshore rigs must be designed using HF/E principles: While technology has enabled more advanced technology and equipment to be utilized in offshore O&G, the interface designs for these systems have not evolved to effectively support the increase in operator load that has been due to greater volumes of data. Poor interface design, where the process controls are not logically organized, the operator is unaware of the system status, and the displays are not intuitive to read, can be a main contributor to operational errors and can lead to potential incidents (Thomas et al., 2002). One of the main challenges facing the O&G offshore industry lies in the lack of integrating human factors principles and methods into the design and implementation of remote sensing and command control systems. Indeed, in the recent Deepwater Horizon investigation report released by the Chemical Safety Board, one of the challenges for the crew was the interface display of the down-hole pressure data (CSB, 2016). Pressure data readings used by the crew to assess well integrity were displayed in a manner that was unclear. Thus, the crew misinterpreted the results of the negative pressure test and considered the properly sealed, unaware that a kick had occurred. Thus, poor interface design was one of the contributing factors in the Macondo incident which led to workers making critical risk decisions based on data obtained from poorly designed controls and displays.

Research is needed on effective training methodologies when Interface Designs are remarkable changed: The implementation of new technology and automation brings changes to the interface design in control rooms and in the field. These drastic modifications have been moving towards integrated instrumentation and systems, with minimal reliance on mechanical gauges and in-field measurements. This brings to fore possible acclimatization issues faced by workers who may have a high level of familiarity with legacy systems (given their experience). Hence research is required for appropriate training considerations for workers / operators to retrofitted facilities that identify challenges and possible gaps in SA. Further, this would yield possible mitigation

measures to prevent lapses during any acclimatization period after retrofit.

5. PROCEDURES

As a part of continuous process improvement, companies are constantly searching for methods to prepare and equip their employees to be able to work safely in the ever-increasingly complex environments of onshore and offshore O&G. Standardizing the methods workers use to perform different processes and tasks is one method of doing this and these standardized methods are often referred to as procedures. Procedures are often more specifically defined as a step-by-step sequence of activities that need to be followed to ensure process and personal safety (Van der Meij & Gellevij, 2004). The effective use of procedures has been identified as a hallmark of Highly Reliable Organizations (Tolk, Cantu, & Beruvides, 2015; Schulman, 1993). The O&G industry devotes an enormous amount of time and money ensuring that workers *e.g.,* can effectively generate, maintain, be trained on, and comply with company operating procedures (Jamieson & Miller, 2000). This dedication of resources is important, however findings from the process industries may need to be applied. Specifically, workers often deviate from or do not use the procedures as intended or expected, and sometimes the procedures are not available to them (Bullemer & Hajdukiewicz, 2004).

According to the root cause analyses of several incidents, inaccurate procedure use contributed to the highest number of incidents in high-risk environments. Bullemer & Hajdukiewicz conducted a study analyzing incident reports at five refinery and chemical plant sites to understand the factors that affect development and use of procedures in industrial environments (Bullemer & Hajdukiewicz, 2004). These investigations explored various types of procedural breakdowns such as incorrect procedures, incorrect use of the procedure, flawed reasoning, and incomplete coverage. Results revealed that approximately 30% of all reported operation failures could be attributed to procedural operations breakdowns, and contribute to a loss in revenue of up to 8% (Bullemer & Hajdukiewicz, 2004).

Another major issue facing effective procedure use has been keeping them up-to-date. If procedures are deemed out-of-date, they have little worth to workers and become a dangerous tool. Furthermore, workers could consider these documents to be unreliable, may overgeneralize, and not seek to use even good procedures to perform their tasks. Jamieson & Miller explored four petrochemical refineries in the US and Canada to see how the culture and organizational factors influenced procedure use (Jamieson & Miller, 2000). Findings suggest that workers did not completely trust their procedures and checklists. This distrust was based on the worker not knowing if or when an update had occurred. Other issues uncovered were the high cost of maintaining procedures, the substantial challenge in making procedures accessible when dealing in large numbers, infrequent use despite investment (a small proportion of worker tasks are overtly completed with a procedure in hand), and regulatory compliance (Jamieson & Miller, 2000).

One of the possible mitigations to maintaining current procedures would be to have workers who use the procedures involved in maintaining their accuracy. Interesting, initial results from a study investigating procedural adherence and acceptance found conflicting evidence regarding this (Peres, Lander, Quddus, Hendricks, Rightmer, Kannan, Ahmed, Tharpe, & Mannan, 2016). In the 69 interviews conducted with workers, many (if not most) indicated that if they did recommend changes to the procedures, they often took at long time to get implemented so many were hesitant to take the effort. Conversely, in a survey of approximately 175 participants who currently use or previously used procedures 93% and 94% respectively indicated that they report inaccuracies and that they make suggestions for changes. Further analysis of these data indicate that for tasks that

require workers check of every step of the procedure, some participant groups indicated that for tasks they performed frequently, they did not look at the procedure over 40% of the time (Peres *et al.*, 2016). There was also a significant negative correlation between workers' experiencing problems with procedures and their perceived safety culture. Finally, 55% of the respondents experienced wishing there were a procedure available when one was not available and 48% experienced being required to use a procedure when they did not think they needed one (Peres *et al.,* 2016).

As for offshore O&G environments, there has been a lack of empirical research concentrating specifically on effective procedure use and/or misuse. However, there have been several incident analyses and investigative reports indicating that inadequate use or misuse of procedures was problematic in offshore catastrophic events such as Piper Alpha and Macondo (Roberts, Flin, & Cleland, 2015; Singh, Jukes, Poblete, & Wittkower, 2010). In the Chief Counsel's Report about the Deepwater Horizon incident, the results indicated that British Petroleum (BP) had inadequate operations procedures (Chief Counsel's Report, 2011) and the report from the Chemical Safety Board Indicated that there was a lack of communication between BP and Halliburton regarding the responsibility for developing the procedures (CSB, 2016). Certainly procedures alone were not the main cause of the incident but seemed to be a contributing factor (Counsel, 2011).

Another study analyzed a sample of 67 offshore incidents and identified the underlying causes from investigation reports and RIDDOR (Reporting of Injuries, Diseases, and Dangerous Occurrences Regulations) reports. Results indicated that one of the most substantial underlying causes of incidents was the lack of or inadequacy of operating procedures. Other causes were poor risk assessments, inadequate supervision, and insufficiencies in permit-to-work (HSL, 2009).

Gaps:
Research needed on how and when written procedures should be used: Based on the literature review, a major issue is that workers often deviate from or do not use the procedures as intended or expected. Empirical research is required to determine the factors that cause these deviations. It is important to know if the deviations are a result of inherent procedure deficiencies or if the procedures are being implemented incorrectly in the environment of use. Further there is an additional need to identify activities that require procedures and when they are required. Procedures may be needed during training, normal operations, or both. Hence there is a need for empirical research to establish true "need – use" pairs for procedures based on existing heuristic knowledge and expertise. These "need-use" pairs have to justify the use of a procedure in a particular scenario and also how they should be used (in hand, memorized, reference, *etc.*). To improve the usability of procedures, research is needed to identify what information operators need to know versus what actions operators need to do in order to complete a task safely and efficiently (based on worker experience, routine vs. non-routine, simple vs. complex, *etc.*). This research will yield an increase in the operational performance and safety in industrial settings.

Industry needs to identify best practices for keeping procedures current: The gap analysis also yielded the need to explore best practices regarding procedure management (*e.g.,* creating, editing, updating, maintaining, accessing). This will likely involve leveraging some of the technological solutions available on the market that allow procedures to be created in a database type format where common elements (*e.g.,* company logos, elements of machinery, series of steps) can easily be duplicated, edited, reused, and updated.

Research needed on the effectiveness of and how to create a culture of ownership for procedure content, format, and use: Procedures form a static interface between the human and machine in an

industrial setting. However, an important function of procedures is also to serve as a layer of protection in a dynamic environment as in the case of an offshore platform. Hence it is important to create a clear channel for open reporting of safety concerns and feedback from front line workers to management (without fear of reprisal or ridicule). Currently, procedure updates may require tedious management of change; research in human interaction with procedures can yield valuable insights on systems that take into account worker feedback. Further, based on the conflicting findings by Peres *et al.* (2016) regarding the perceived engagement with ensuring procedures were correct, this suggests that it is paramount to create an environment where workers identify the importance of speaking up and editing procedures—where workers feel they have valid input that will be taken into seriously, and that their opinion matters.

6. RISK PERCEPTION

For engineers and managers, identifying and mitigating risks—operational, safety, and environmental—in O&G essentially involves identifying three things: what can go wrong; the probability of that event happening; and the severity of that event. After the Piper Alpha disaster in 1988, the Health and Safety Executive (1992) required operators to identify major hazards to reduce risks on offshore facilities. Typically Quantitative Risk Assessment (QRA) is the primary tool used by engineers and managers to assess these risks, however workers often do not base their judgment or perception of risk on severity and probability of consequences, which may be why workers behavior does not match what the engineers and managers typically expect.

To better understand risk perception of workers in offshore platforms, Flin *et al.* conducted a survey on risk perceptions of major hazard and risks and compared these perceptions to QRA analyses for several different platforms (Flin, Mearns, Gordon, & Fleming, 1996). They found that the workers on the installations for which the QRA calculations showed less risk reported perceiving less risk than the workers in the "higher risk" installations. Interestingly, experienced workers perceived less risk overall. However, the study could not conclude whether this lower level of risk perception among more experienced workers was representing a more accurate awareness of the risk or more complacency about possible risks. Specifically the researchers were not able to identify an optimal "risk awareness level" for offshore platforms and answer questions on whether the workers underestimate the risk and how safety culture and attitude affect risk taking behavior *etc*. (Flin et al., 1996).

Rundmo also performed survey for evaluating risk perception regarding the physical working conditions, job stress, potential risk, and safety and contingency factors (Rundmo, 1992). The survey was conducted in eight installations on the Norwegian Continental Shelf. The study showed that frequency of human error and incidents was related to risk perception and job stress. Specifically, bad working conditions and an absence of proper contingency and safety measures made the workers feel unsafe. The study concluded that safety measures developed toward improving working condition would change risk perception among workers was also predictive of incidents/near incidents (Rundmo, 1992). Rundmo *et al.* conducted a similar survey to identify how the risk perception had changed from 1990 to 1994 (Rundmo, 1992). The study found that the working conditions improved which improved the risk perception compared to the previous result. However, management and employees seemed less involved and committed toward safety.

Gaps:
Further research is needed regarding the relationship between organizational factors, risk perception, and performance & safety: According to the study conducted by Flin *et al.*, there is need of further research into identifying what is the accuracy of risk perception among workers in offshore O&G (Flin et al., 1996). There has been little investigation toward understanding the

effect of organizational factors and work-load on risk perception and overall safety and how a safety program can be designed to account for risk perception. Researchers need to conduct studies on how safety attitude, managerial factors (*e.g.,* production over safety attitude) effect the actual risk perception of worker and risk-taking behavior and most importantly, how risk perception affects human performance and safety.

7. STRESS

Stress is a response to a stimulus or stressor that affects our physical or mental equilibrium or well-being. The stressors that trigger the response may include: environmental stressors, chemical stressors, social stressors, workplace stressors. Several studies have been conducted relating various predictors for stress (stressors) in the O&G working environment such as physical working and environmental conditions, work schedule, personality trait, and mental health, all of which influence the workers' physical and mental capacity, workload, incident rates, and perceived risk.

Some of the studies have examined various combinations of physical or environmental stressors that offshore workers experience. The stressors include confinements, vessel movements, workplace hazards, negative weather conditions, and high workloads (Rodrigues, Fischer, & Brito, 2001), noise, lighting, vibration, and small living spaces (Parkes, 1998), ergonomic, climatic, and chemical conditions (Rundmo, 1992), and noise, vibrations, draft and cold (Rundmo, Hestad, & Ulleberg, 1998). Such stressors are related to higher workload (Rundmo et al., 1998) or strain, both of which increase the probability of injuries (Rundmo, 1992). In addition, the prevalence of major incidents in offshore drilling is also a stressor to many workers (Rodrigues et al., 2001).

Workers consider their time away from home to be a stressor as well; several findings also indicated that work-family conflict was increased with offshore shift work (Parkes, 1998; Rodrigues et al., 2001). For example, workers reported taking as long as three days to "re-adapt" after arriving at home. Similarly, the last days during time off are characterized by negative feelings, often referred to as "pre-boarding stress syndrome" (Rodrigues et al., 2001). Other stressors related to shiftwork offshore include: poor sleep, fatigue due to previous work on board, long commuting time, and domestic problems (Rodrigues et al., 2001). Some of the major features of shift work schedules are long time on board (14 to 28 days), long shifts (12 hours or more per day), long sequence of days on a particular shift (7 to 14 days in a row), and extended journeys for shift change and landing (18 hours). These features of a typical offshore work schedule provide many opportunities for stress to influence the worker.

Sutherland & Cooper studied the relationships among certain personality traits, stress, and incident involvement as an outcome (1991). Results indicated that those with Type A behavior styles (*i.e.*, competitive, ambitious, impatient, aggressive, fast talking) reported significantly higher incident/near-miss involvements than Type B's (*i.e.*, relaxed, non-competitive). Persons with Type A behavior personality also tended to report more stressors (*e.g.*, high workload and role conflict) (Chen, Wong, Yu, Lin, & Cooper, 2003). Results are still not clear on causal links. For example, it could be that Type A's take on more work generally, and thus, are at a risk for higher incident involvement. The authors talk about selection for offshore positions including consideration of personality traits because it is clear these traits are associated with job performance and other relevant outcomes (*e.g.*, incident involvement, job stress, and mental health). Chen and colleagues found that workers with college/university-level education perceived more stress from work-family conflict than others (Chen et al., 2003). Another study showed that while the mental health of onshore and offshore workers tend to be similar, offshore

workers experience higher levels of anxiety (Parkes, 1998). Fortunately, Chen *et al.* concluded that social support could mitigate the effects of stressors (Chen et al., 2003).

Crichton assessed current attitudes towards stress in offshore workers (Crichton, 2005). Surprisingly, only a third of workers (34%) indicated that their performance is affected by stress. Training may be able to help educate employees about the limits of human performance (physically and mentally) under stress. Wong *et al.* identified nine sources of perceived stress for offshore workers in China: physical environment, safety, interface between job and family life, career and achievement, organizational structure and climate, living environment, ergonomics, management problems and relationships with others at work, and managerial roles (Wong, Chen, Yu, Lin, & Cooper, 2002). Here, sources of stress for Chinese workers were found to be different from those of offshore workers in the UK. Wong *et al.* concluded that this is likely due to socio-cultural differences (Wong et al., 2002). Interestingly, it was reported that there is an inverse relationship between age and perceived stress from "organizational structure"(Chen et al., 2003).

Job stress and perceived risk are factors that increase workload and increased workload can lead to increased stress and strain and a decrease in the ability to cope in dangerous situations. Thus, perceived risk is also a stressor for offshore workers (Parkes, 1998). Stress can reduce working memory capacity as well as attention (Hancock & Szalma, 2008). As a result, stress has been found to significantly reduce SA (Sneddon, Mearns, & Flin, 2013). Further, stress offshore can take the form of physical pain in different body regions (*e.g.*, musculoskeletal pain) (Chen, Yu, & Wong, 2005).

Gaps:
Experimental and/or longitudinal studies need to be conducted to determine causes of and effective mitigations for stressors offshore: Most of the studies about stress were performed as a cross-sectional survey at a specific time hence they provide only a snapshot (Chen et al., 2005). As Parkes *et al.* suggested a series of research studies over a long-term period will provide more reliable information of mental and physical health of those working offshore (Parkes, 1998). In addition, such time series analysis can help reveal the causal relationship among stressors, cognitive capacity, and safety performance; for example, how sleep pattern changes risk perception and affects safety performance. More longitudinal studies are required for reliable information on offshore personnel's mental and physical health. A standard assessment method for measuring stress level should be sought. As suggested by Wong *et al.* research over different cultural settings will enhance our understanding about the effect of socio-cultural characteristics on the perception of stressors (Wong et al., 2002).

8. FATIGUE
Fatigue is a multidimensional construct and it can be generally defined as a physiological state of reduced capability of mental or physical performance that is a result of sleep problems, circadian phases, and physical or cognitive workload. Indeed, it has been implicated as a serious risk factor in many cases affecting worker safety (Chan 2011; Mason, Retzer, Hill, & Lincoln, 2015; Retzer, Hill, & Pratt, 2013). Oil field workers are often continuously exposed to many of the conditions that may result in fatigue. These include: long working hours, shift-swings (*i.e.*, changing from night shift to day shift or vice versa), heavy physical work, intense cognitive load, hazardous work environments, heat and cold stress, noisy environments, psychosocial stressors, a lack of privacy, and isolated work locations.

Given the isolated nature of the offshore environment, the work schedules are necessarily different than those onshore. In a qualitative study, workers on an offshore drilling unit were

interviewed about their experiences with their schedules (RODRIGUES et al., 2001). The main features of a typical offshore work schedule provide many opportunities to influence the worker's fatigue, such as stress, as described above. In addition, shift-work and night-shifts have been linked to negative psychological and health outcomes, including sleep issues such as fatigue, tiredness, and other sleep problems (Menezes, Nogueira Pires, Benedito-Silva, & Tufik, 2004). Shift/nighttime workers experience more negative sleep outcomes than daytime workers (*e.g.*, poorer quality of sleep, more difficulty falling asleep) in addition to negative health outcomes (*e.g.,* depressive symptoms). One study found that compared to day-shift workers, both night-shift and swing-shift workers reported lower sleep quality on the first day of the leave period (Merkus et al., 2015). Parkes (2012) reached a similar conclusion that circadian disruption can negatively impact initial night shifts, and that complete adaptation (i.e., physiological and psychological responses) occurs within 5–6 days. Moreover, the author noted that the re-adaptation to day shifts were slower and that it varied widely across operators. Hansen et al., (2010) used several physiological indicators of fatigue collected from day and night shift offshore workers to understand the the impact of shift work over 7 days during circadian adaptation. The study reported an increase in core body temperature over time in night shift workers, which indicated an adaptation in the night workers to new working schedules, but found no changes in heart rate and blood pressure. Overall, fatigue is known to decrease alertness and increase risk of incident occurrence (HSE, 2006), particularly at the end of the offshore working cycle (Valentić et al., 2005). In addition, fatigue has been shown to predict lower SA (Sneddon et al., 2013).

In a comparison of onshore and offshore workers' sleep quality and sleep duration, Parkes found that the onshore night-shift workers experienced lower quality sleep compared to onshore day-shift workers, but this difference was not found among offshore workers (Parkes, 1994). For both on and offshore workers, age was found to be negatively related to sleep duration and sleep quality, suggesting that older workers have more difficulty adjusting to shiftwork. Parkes also found that experience with shiftwork was negatively related to sleep duration that is more experienced workers had more difficulty sleeping. These findings suggest that shiftwork might have a cumulative and adverse effect on sleeping a sufficient amount of time. However, experience with shiftwork was not a predictor of sleep quality. Finally, neuroticism was also negatively related to sleep quality and sleep duration, specifically, those high in neuroticism reported shorter sleep duration and poorer quality sleep than those low in neuroticism. Taken together, these findings suggest that in offshore environments there may, in fact, be a floor effect where everyone has sleep problems, regardless of the variables that effect sleep onshore (Parkes, 1994). On the other hand, Waage et al., (2013) followed 188 offshore workers, assigned to day- or swing-shifts, through their 2-week offshore working cycles and reported that at the end of the work cycle a higher proportion of insomniacs were seen among swing shift workers compared with day workers, while subjective health responses on sleep quality did not differ between the two groups. In another study, Waage et al. (2012) followed 19 offshore workers, across day, night, and swing shifts and evaluated fatigue due to sleepiness using subjective and objective measures. While objective measure of sleepiness, measured using reaction times, did not change between shift types, the study reported increased subjective sleepiness during the first days of night shift work, and in the first days and middle of the swing shift work period. Moreover, night shift work was associated with greater subjective sleepiness being carried over after returning home than after working day or swing shifts. For the same study cohort, Harris et al. (2010) tested changes in diurnal (cortisol) rhythm to understand recovery from different shift types. Night shift was associated with longer recovery measured using cortisol rhythm. Additionally, while cortisol rhythm returned towards a normal rhythm in the second week for the swing shift workers, complete recovery was not observed even after the workers returned home. Subjective recovery and performance were not impacted by shift type. Collectively, these studies emphasize that the workers are able to adapt to their circadian rhythm without compromising on performance and do

not perceive lack of sleepiness or recovery from fatigue, and that the effects of fatigue due to shift work may have a consequence on their long-term health outcomes.

The UK Health and Safety Executive has made recommendations to mitigate the effects of fatigue and those are associated with the amount of time someone can work during a given duration (HSE, 2006). Specifically, any one shift should not exceed 14 hours (12 hours standard work plus 2 hours overtime), and that overtime on consecutive shifts should be avoided. Under this guidance, a worker may work only about 7 hours of overtime per week (2 hours of overtime per shift on alternating days). In a study by Parkes, 84% of the overtime group reported working more than 7 hours of overtime, which suggests that the HSE guidelines are not being followed in most cases (Parkes, 2015). Further, there are not any known empirical studies to determine if/when this guidance is followed or if there were any positive effects on fatigue levels.

Gaps:
The effects of offshore work schedules, which include overtime and irregular work patterns, on fatigue and both acute and chronic health of workers is understudied. More research is needed on contributors to fatigue beyond sleep and shift: Given the detrimental effects of fatigue on worker outcomes (*e.g.*, performance and health outcomes), it is important to understand how fatigue affects performance, especially the aspects of the offshore working environment that are related to fatigue, and how fatigue can be mitigated to reduce its effects on performance. However, the current knowledge with regard to understanding these issues are inconsistent and limited to sleep and circadian issues. Additionally, there is little understanding of the specific and cumulative effects of physical and cognitive load on fatigue and the effects of fatigue on operator performance.

More assessment methods are needed to effectively measure fatigue in the offshore environment: For more accurate measurement, use of actigraphic recording devices, measuring salivary cortisol (Merkus et al., 2015), and independent collection of overtime hours from a company's database are suggested as a means of complementing the self-completion survey (Parkes, 2015). Though the association between long work hours, *i.e.*, overtime, and sleep disturbance is investigated (Parkes, 2015), how other factors such as personality characteristics (*e.g.*, morningness/eveningness chronotype, neuroticism, and extraversion/introversion) affect sleeping need further research effort (Saksvik, Bjorvatn, Hetland, Sandal, & Pallesen, 2011).

Finally, translational research studies that develop and test fatigue mitigation interventions are lacking. Studies that target intervention design and testing to improve circadian re-adaptation to reduce fatigue due to lack of sleep quality or to reduce operator physical and cognitive fatigue by developing effective work design and practices can significantly reduce fatigue-related incidents/accidents in the offshore rig environment. The ANSI/SPI Recommended Practice (RP) 755 provides guidance for personnel in the petroleum and petrochemical industry in term of understanding, recognizing and managing fatigue in the workplace (API, 2010). It is a direct result of the BP Texas City Incident of 2005, where the Chemical Safety Board's accident investigations determined fatigue was a contributing factor as some operators had been working 12-hour shift for as many as 29 days consecutively. The RP 755 was developed for refineries, petrochemical and chemical operations, natural gas liquefaction places, and other facilities covered by the OSHA Process Safety Management Standard and is intended for a workforce that is commuting daily. Currently there are no fatigue-related practice for off-shore rigs or any facility where employees are housed on-site.

9. SITUATION AWARENESS

A key element for workers maintaining safety in high-risk environments is their ability to maintain situation awareness (SA) (Bullemer & Reising, 2013). According to Endsley, SA is the continuous awareness that a person has in a situation, or a worker's dynamic understanding of what is going on around them (Endsley, 1995). One of the more popular models of SA is Endsley's three-level model. The distinct levels of SA in this model are (Endsley, 1995):

Level 1 – Perception (scanning, detecting cues, gathering data)
Level 2 – Comprehension (understanding, creating mental model)
Level 3 – Projection (ability to correctly forecast possible future circumstances).

Improving worker SA has become an important objective when designing and developing operation interfaces, automated technology, and training programs throughout many domains such as aviation, nuclear, O&G, and manufacturing (Endsley & Garland, 2000). In a study involving multiple aviation incidents, approximately 88% of human errors could be attributed to issues related to SA (Endsley, 1995).

Sneddon *et al.* found that loss of SA (*e.g.*, level 1 - loss of concentration, distraction) had been frequently identified as the issue in many of the incident reports from the offshore industry (Sneddon, Mearns, & Flin, 2006b). Kaber & Endsley theorized that performance and safety issues taking place in the process safety and control domain are directly and indirectly related to difficulties with an workers' SA and therefore the researchers sought to identify the influences in the environment that were impactful on the worker (Kaber & Endsley, 1998). Their study found that external influences impacting human performance were workload, fatigue, and stress. Another study reported similar results, which focused on work SA in drilling personnel. Results showed that higher levels of fatigue and stress were significantly correlated with low levels of SA, which could lead to unsafe behavior and increased incidents (Sneddon et al., 2013). Low SA or lack of SA has been postulated as a causal factor in many incidents. One study examined the role that SA played in three process incidents. Incident analyses and investigative reports revealed that the cause of the incident was not related to poor decision-making, but rather the absence of SA and poor mental models (Naderpour et al., 2015). Several other studies have reported finding the loss of SA can result from something as simple as inattention and is also a function of experience and training (De Cort, 2015; Sneddon et al., 2006b).

Several research studies have addressed the topic of SA in offshore environments by identifying the proportion of SA errors prevalent in drilling incidents to gain an understanding of the main issues underlying SA. Kiani *et al.* conducted a cross-sectional study examining occupational SA, safety climate, and fatalistic beliefs (Kiani, Borjali, Farahbakhsh, & Farrokhi, 2013). Results showed that workers' beliefs in fatalism and safety climate were significantly associated with their occupational SA (predicting almost 18% and 20% of the variance, respectively). The integration of these constructs into safety interventions, as well as prevention and coping methods, could increase workers' SA. Thus, considering these variables may be important for explaining and predicting work SA as well as for driving more obvious safety outcomes such as safe behaviors.

Another study investigating offshore drilling incidents that occurred within the period January-October 2003 found similar results (Sneddon, Mearns, & Flin, 2006a) Of the 332 incidents, 135 were related to SA, and more than 40% of drilling activity incidents were associated with inadequate SA. A majority of those errors (67%) occurred at Level 1 SA, 20% took place at Level 2 SA, and 13% were Level 3 SA (Sneddon et al., 2006a). Interestingly, the frequencies of SA errors (Levels 1, 2, & 3) appearing in both aviation and maritime shipping industries were similar to those in offshore O&G drilling industry. There is a likelihood that these frequency patterns

could extend to other high-risk domains (Sneddon et al., 2006a).

Finally, in a recent study by Roberts *et al.,* a content analysis was conducted of SA components related to crewmembers' accounts of their actions during the two negative pressure test (NPT) phases associated with Macondo (2015). The authors sought to validate a model and investigate why the crew erroneously concluded that the well was stable when it was not. An analysis of well control simulator observations and interviews with drill crewmembers were used to develop the prototype Driller's Situation Awareness model framework. The model was then applied to cognitive data extracted from a given period (3 pm – 8 pm) several hours before the blowout. Analysis of SA in the drilling incidents indicated problems with "Level 1: missing information" (9.7%) and failures to monitor data (26.8%), as well as "Level 2: errors relating to mental models" (20%). Other influencing factors identified were workload, work environment, distractors, and experience. Fatigue was briefly mentioned in the reports but was not designated as a significant factor. Evidence in reports suggests that crewmembers detected some of the available cues despite missing key information. Another important outcome was the fact that the crew misunderstood the significance of the cues based on their mental models of the well state. These analyses highlight how an inaccurate mental model and resulting expectations can impact successive cycles of SA, influencing the interpretation of cues and how the situation is anticipated to develop (Roberts et al., 2015).

Gaps:
More research is needed to determine the causal relationships between the elements offshore and decreased SA using alternative methods of measuring SA: An offshore drilling rig and production platform is a dynamic environment. The constant threat of change demands workers to continually monitor and assess their situation. Drilling crews have to work together to perform drilling operations such as building and maintaining well integrity. There is a dearth of evidence surrounding SA in the O&G industry. Therefore, future research should focus on SA through behavioral markers in the offshore O&G, specifically identifying key factors associated with ineffective operations and team SA. A study conducted by the Abnormal Situation Management Consortium (ASMC) investigated team SA in major process safety incidents. Results showed that half of operations practice failures across 32 incident reports involved failures associated with team SA (Bullemer & Reising, 2013).

Further research is needed to identify the external influences of fatigue and stress on workers' SA: Workers in O&G operations experience continued exposure to physical, cognitive, and psychosocial stressors, which can further increase fatigue, reduce SA, and impede cognitive performance. Low SA or the lack of SA has been hypothesized as a causal factor in many incidents. Higher levels of fatigue and stress were significantly correlated with low levels of SA, which could lead to unsafe behavior and increased incidents (Sneddon et al., 2013).

Safety interventions need to include variables that increase worker's SA: Several studies have addressed the topic of SA in offshore environments by identifying the proportion of SA errors prevalent in drilling incidents to gain an understanding of the main issues underlying SA within the drilling industry. Kiani *et al.* conducted a cross-sectional study examining occupational SA, safety climate, and fatalistic beliefs (Kiani et al., 2013). As we observed above, the results showed that workers' beliefs in fatalism and safety climate were significantly associated with their occupational SA. The integration of these constructs into safety interventions, as well as prevention and coping methods, could increase workers' SA. Thus, considering these variables may be important for explaining and predicting work SA as well as more obvious safety outcomes such as safe behaviors.

Interface and human-machine interaction designs that are associated with SA (either improved or impaired) need to be identified through research and implemented offshore: As mentioned above, SA can serve as a predictor of performance and is particularly important in the interface designs where technical and situational complexity impact the decision-making efforts of the human. SA has been acknowledged as the basis for good decision making within complex systems, including the O&G industry where poor performance can lead to devastating results.

10. ALARM MANAGEMENT

The need for alarm management has resulted from the ease with which alarms can now be associated with values for managing and monitoring systems processes. This has led to situation such as, an unplanned work stoppage in a process can cause a system to elicit over 1,000 alarms per minute (Sanchez-Pi, Leme, & Garcia, 2015). This "alarm flood" impedes the ability of workers to distinguish between different types of alarms and to take the necessary action (Sanchez-Pi et al., 2015). By ANSI/ISA 18.2 standards, an alarm flood occurs when there are 10 or more alarms in a 10-minute period (ANSI/ISA, 2009). The information overflow that results has been linked to several major incidents. For example, a Health and Safety Executive indicated that the workers' inability to decipher the significance of the alarms was related to the cause of the incident of the Milford Haven refinery incident in the UK in 1994 (HSE, 1997). In 2013, Al-Azmi & Parikh identified poor alarm management as "one of the key contributing factors to the seriousness of process upsets and incidents" in the West Kuwait Oil Field (Al-Azmi & Parikh, 2013). The incident at Three Mile Island is a well-known example of a time when alarms were inefficient, and this contributed in large part to a major catastrophe (Wilson, 1998).

A study by Woodcock & Au indicated that alarm systems are often the primary source of information (*e.g.*, daily operations and emergency events) for offshore control room workers (CROs) (Woodcock & Au, 2013). Thus, alarms clearly need to be efficient and effective sources of information, especially in abnormal/emergency situations. Many alarm systems convey *too much* information, *i.e.*, "alarm flooding," for the CROs to process, which creates a high workload (Woodcock & Au, 2013). This overload may impede identification of the event and subsequent communication to other workers. In addition, with an overabundance of alarms, workers can become desensitized to the alarms and not attend to them at all. This type of reaction is clearly detrimental in a situation that requires immediate attention.

One particular research study looked at an alarm management system (AMS) for offshore that may provide a solution to workers' SA issues during emergencies (Sanchez-Pi et al., 2015). This AMS is a multi-agent based approach used in assisting workers to make sense of many alarms simultaneously (García, Leme, Pinto, & Sanchez-Pi, 2012). Specifically, the Ambient Intelligence System (AIS) has interconnected sensors and devices that integrate information from various areas of the petroleum plant environment. It gives workers real-time information and accumulated historical data, which helps provide flexible yet intelligent services to workers. Most importantly, this connectedness allows for the AIS to make decisions about what information the CROs do and do not need. Initial studies show that the system suppressed 94% of the alarms (from the alarm flood) and that workers confirmed the information from these systems was not necessary.

Gaps:
Empirical research studies need to be conducted to identify effective alarm rationalization and presentation methodologies: Although the problem of alarm management has been clearly identified by the industry, there have been no substantive studies to confirm that the information provided by the system gives the control room operators (CRO) the information they need, when they need it, and in a manner that is easily understood. Applied research is needed regarding how

alarm rationalization techniques can be successfully useful in offshore environment (Al-Azmi & Parikh, 2013; Beebe, Ferrer, & Logerot, 2012) and regarding the type of decision support tools that will best support CROs based on human cognitive capacity (Adhitya, Cheng, Lee, & Srinivasan, 2014). Continuing research is needed to develop systems to support workers' being able to distinguish between different types of alarms during an emergency and act accordingly, alarms in systems such as ambient intelligent system design with appropriate operator intervention. Indeed, refining has some promising work in alarm management that could be directly applied to drilling, both on and offshore. Adhitya and colleagues developed and tested an alarm management approach that utilized an "Early Warning" decision support system (Adhitya et al., 2014). They found that workers were able to notice problems more quickly than without the alarm but not identify the type of problem. Similarly, Beebe *et al.* analyzed the benefits of different types of alarm management programs and found that dynamic alarm management significantly reduced the number of alarms and increased the quality of information provided by the alarms displayed (Beebe et al., 2012).

11. AUTOMATION

Automation is a method of leveraging control systems in a manner so that the human is not required to intervene for a process to run effectively. Automation is of particular relevance to high-risk industries, such as O&G, chemical and nuclear energy, and transportation (Flaspöler et al., 2009). In offshore drilling, the level of automation has gradually increased over the past several decades and this expansion has helped to increase task efficiency and decrease worker workload (Ciavarelli, 2016). This increase has changed the way workers perform their tasks from manually operated machinery to computer-based integrated systems. The goals of these automated systems are to improve quality, safety, and performance (Skogdalen & Smogeli, 2011).

However, this increased automation and the increased complexity of machine design means that CROs have to handle complex data and alarms while under pressure to make safety-critical decisions based on unanticipated and varying hazardous situations (Flaspöler et al., 2009). In simple automation, the human manual control is replaced by an automatic controller that may or may not require a human to be present. However, in highly automated systems it is typically essential for workers to be present to supervise, monitor, adjust, maintain, and enhance the processes as there are many elements of these systems (Ponsa et al., 2010). Effective HMI designs for differing levels of automation to ensure SA and facilitate effective emergency response is a major risk for the offshore industry and there is little to no research regarding this topic for the offshore O&G environment.

The aviation industry has proven there are risks and difficulties associated with replacing human worker functions with high levels of automation. Some risks related to advanced automation are associated with worker complacency and confusion (Ciavarelli, 2016; Lee, 2008). Complacency occurs when the trust in automation is high, but in fact the automation is unreliable and leads to overreliance and failure to monitor data input while allocating attention away from the automated task (Parasuraman & Wickens, 2008). Operators can experience a reduction in cognitive involvement or interest in tasks, which brings about passive monitoring and in turn compromises worker SA. Operators with low SA may find it challenging to reorient themselves to the system in time to prevent failure or unpredicted events (Endsley, 1996) and this is often confused with complacency. Confusion occurs when a worker misinterprets the observed behavior of the operating system in light of their mental model of the systems. This confusion can occur regardless of whether the system is operating properly or not. The level of complexity and operations performed by the user can lead to a failure in correctly identifying the current

operational state of the system. Failures such as these can yield a high potential for erroneous error input by the worker (Ciavarelli, 2016). These risks factors reduce SA and could lead the workers into a potentially hazardous situation (Lee, 2008).

There are exciting new developments based on the continued advancements of automation technology. For example, Norway's Drilling Systems are designing and will implement robots to perform repetitious tasks being completed currently by pipe handlers and roughnecks (Weaver, 2014). Another area of expected growth is in the application of remote sensing and controls systems. These systems are used for a variety of operations such as observing and obtaining measurements, conducting well integrity tests, and presenting display systems for operations and exploration. These are additional examples of automated systems that—due to their highly complex nature—if not designed incorporating effective HFE methodologies, can give rise to the real possibility of operational errors (Ciavarelli, 2016).

Various challenges are facing the future of offshore O&G operations. An important issue challenging the industry is the propensity towards overuse of automation. As the use of automated technologies increases, there will be a desire to decrease worker workload and eliminate human error. The focus of automation should be centered on achieving the most effective balance between humans and machines (Flemisch et al., 2012). Another challenge lies in the lack of incorporating human factors methodologies into the design and implementation of remote sensing and command control systems. These systems need to include human factors in order for the design processes to help mitigate potential errors (Ciavarelli, 2016). Indeed, as mentioned previously, current research by Endsley suggests that many of the automation tables being leveraged by O&G and others may be grossly misrepresenting how HMIs for automation should be designed (Endsley, in press).

Gaps:
Research needs to be conducted to update current "automation tables" being leverage by automated systems used offshore: One of the major challenges with the automation of drilling and subsea systems is identifying the balance between automation and human interaction. The focus of automation should be centered on achieving the most effective balance between humans and machines (Flemisch et al., 2012). With the current propensity towards overusing automated technologies, there is a certain need for identifying the correct balance between automation and human interventions for better performance. Before adding automated features to a system, probable impacts on human performance need to be assessed and examined carefully.

The interactions between automation and SA need to be fully understood through research studies, particularly how this may be relevant for emergency situations: Developing a framework correlating automation complexity with SA could also be useful to identify potential causes of conflicts. Currently there is a gap in our understanding of how exactly an increased level of automation impairs SA in the context of offshore drilling. Such study would allow establishing a correlation between these two and providing recommendation for effective implementation of automated technologies. There is also a clear need for conducting fundamental studies on how automation would help to improve safety performances of drilling or operational activities. Introducing automation may reduce normal operational risk and uncertainties associated with human functions but it could also introduce unprecedented complexities and may lead towards abnormal scenarios. Another important aspect of this potential research area would be effective integration of automated response technologies during an emergency to achieve improved SA and minimize negative consequences.

12. SAFETY CULTURE/CLIMATE

In 2013, Smith and his colleagues outlined 25 specific errors that led to the Macondo incident in the Gulf of Mexico (Smith, Kincannon, Lehnert, Wang, & D Larrañaga, 2013). They further articulated that most of these errors were latent errors caused by poor leadership resulting from a poor safety culture. The culture of an organization is characterized as the values, beliefs, and underlying assumptions of an organization. This differs from the climate of an organization, which is considered the employees' perceptions and experiences of the organizational atmosphere and is more about how safety behaviors actually occur in the workplace (González-Romá, Peiró, Lloret, & Zornoza, 1999). Safety climate is also considered an indicator of the underlying safety culture of a work group, plant, or organization. Given that climate is more directly related to the state of safety in workplace, we discuss here the research related to this construct specifically in the offshore environment.

One of the first challenges for researchers wanting to investigate the implications of safety climate is identifying reliable and effective methods to measure it. In 2000, Cox & Cheyne developed an assessment method called the Safety Climate Assessment Toolkit (Cox & Cheyne, 2000). This method was based on a systems approach to organizational culture and combines a number of assessment techniques, including: questionnaires, focus groups, behavioral observations, and situational audits. Together, these varied methods provided different and complementary views of organizational health. The authors' position was that the immediate benefits to using this safety climate toolkit were not only the profiling of safety climate but also subsequent action planning. ABS has also generated methods of measuring safety culture and climate and has specific methods available for leveraging these as leading indicators of safety (ABS, 2014a).

Mearns *et al.* surveyed 722 employees on 10 offshore installations and found that workers generally felt their safety climate was positive and conducive to safety (Mearns, Flin, Gordon, & Fleming, 1998). Overall, respondents expressed positive attitudes regarding management commitment to safety, and negative attitudes towards violations of rules and procedures to get the job done.

There have also been a few studies specifically focused on the whether the attributes of safety climate were related to some safety outcomes in the offshore environment. For example, Flin *et al.* conducted a qualitative study looking at safety climate offshore (measured using the Offshore Safety Questionnaire, OSQ) (Flin, Mearns, Gordon, & Fleming, 1998) and its relationship with specific safety behaviors and found few participants reporting they behaved in unsafe ways. Indeed, the majority of participants indicated they never engage in forbidden activities. However, about half of them responded they "seldom/sometimes" ignore safety regulations to get the job done, break work procedures, or bend the rules to achieve the target. Regression analysis found that "attitude to violations" and "work pressure" were the two factors that best predicted self-report frequency of these unsafe behavior. One challenge with this study was the low rate of self-reported unsafe behavior. It is possible though that the respondents did not feel they could honestly respond without repercussion and thus the negativity of these findings could be understated.

In another study examining climate, safe, and unsafe behavior, Mearns *et al.* examined the relationship between management safety practices and incident involvement (Mearns, Whitaker, & Flin, 2003). These researchers found that a part of management practices called management commitment (*i.e*., managerial safety performance, number and reason behind visits by senior onshore personnel, and priority of safety at routine management meetings) was significantly predictive of lower incident rates as well as lower official incident reports. However, only partial

support was found for the linkage between safety climate and incident rates. In another study (mentioned above), fatalistic beliefs (views on importance and control of safety hazards) were examined in addition to safety climate (Kiani et al., 2013) and the study found that both safety climate and fatalistic beliefs (all self-reported) were significantly related to work SA (almost 20% and 18% of the variance in occupational SA, respectively). Therefore, a consideration of these variables may be important for explaining and predicting work SA as well as more obvious safety outcomes such as safe behaviors.

The importance of local leadership to the safety culture offshore has also been examined. For example, the site location seemed to be more predictive of safety climate than the company in which people (both employees and contractors) were employed (Høivik, Tharaldsen, Baste, & Moen, 2009). This suggests that the local supervisors at each particular installation have a greater influence on safety climate than more distant/higher-level management does. In addition, another study focused on examining the relationship between leadership styles (both constructive and destructive) and safety climate (Nielsen, Skogstad, Matthiesen, & Einarsen, 2016). Findings indicated that constructive leadership is positively related to safety climate, while destructive forms of leadership (both laissez-faire and tyrannical leadership) were negatively related to safety climate.

One study focused on Offshore Installation Managers (OIMs) and surveyed this group about leadership and safety in the offshore O&G industry (O'Dea & Flin, 2001). Results indicated that managers tend to know best practices in safety leadership, but do not always act consistently with these best practices. In addition, managers report difficulty in motivating employees and controlling certain aspects related to safety in their workforce, such as getting employees to accept ownership of safety and getting them to report near misses.

This summary indicates that safety climate (and culture) has important implications for safety in the offshore environment. Specifically, safety climate is related to safety management practices (*e.g.*, health screenings, safety awareness initiatives) and this is correlated to incident rates (Mearns et al., 2003). Some of the research presented here suggested that leadership (particularly local) has direct impacts on safety climate (Nielsen et al., 2016; O'Dea & Flin, 2001) although some leadership groups (*e.g.,* OIMS) were not consistently practicing safety leadership and were unsure regarding how to motivate safe behavior in their workers (O'Dea & Flin, 2001). This suggests that training and empowering immediate supervisors and mid-level managers may be as important as the training for front line workers and more senior-level leadership.

Gaps:
Research studies leveraging more objective and longitudinal methods need to be employed to explore causal relationships regarding safety climate and culture: Some of the challenges with this research is that the measures of safety climate are self-reported and all of the relationships reported here are correlational in nature and therefore do not necessarily indicate causal relationships. To better understand the causal relationships between safety climate and safety outcomes, future research should focus on methods of ensuring the reliability of the self-reports used to measure safety climate and also on working with industry partners to conduct experimental methodologies to identify causal relationships, *i.e.*, employ pre-post intervention measurement or an intervention and comparison groups. Having a better understanding of the causal relationships between the variables identified is one way to improve safety culture, safety practices, and ultimately safety outcomes on an offshore facility.

Research efforts need to be placed on finding out what factors hinder or facilitate the formation, development, or deterioration of safety culture/climate in offshore facilities: As workforces in

offshore installations are typically experienced with frequent shift change and relatively long period of leave, fostering safety culture/climate in such circumstances is forecast to be challenging. Exploratory research questions could start with inquires about human and ergonomics factors such as stressors, fatigue, noise, and lighting. In addition, organizational aspects should be taken into consideration to determine the impact of different leadership styles, existence of blame culture, and the like. According to Pilbeam *et al.* most of the studies that measured leadership did so through generic scales (Pilbeam, Doherty, Davidson, & Denyer, 2016). They recommended using alternative methods to enrich our understanding of safety leadership.

13. *QUANTITATIVE RISK ANALYSIS*
Quantitative Risk Assessment (QRA) covers a wide spectrum of risk assessment methodology and many endeavors to translate HF/E into QRA have been explored. This section of the paper briefly introduces the framework for risk assessment for HF/E elements, such as HF engineering, Human and Organizational Factors (HOFs), and Performance Shaping Factors (PSF), specifically for the offshore O&G industry. There are various tools, such as Bayesian Networks (BN) and Human Reliability Assessments (HRA), for quantifying and integrating these elements into a risk assessment framework.

Incorporating Human Factors and Ergonomics: Offshore installations operate in a dynamic environment in which technical and human and organizational malfunctions may cause incidents. This requires safety engineers and risk analysts to take HOFs into account as well as technical aspects of design, construction, and operation. Modeling the possible relationships among all of these risk factors increases people's ability to address latent failures within the causal sequence of events and reduce the risks of incidents occurring.

One of the limitations of QRA has been the failure to incorporate HOFs. Skogdalen *et al.* conducted a study on 15 QRA methods and divided QRA approaches into four levels (Skogdalen & Vinnem, 2011). As seen in Table 2, level 1 QRA methods do not incorporate HOFs at all; level 2 gives some degree of attention to HOF and level 3 adjusts the QRA model to include HOFs. Level 4 is the ideal level with QRA incorporated in the core of safety and risk assessment. Unfortunately, none of the analyses fulfilled the requirement of the highest level of QRA and hence calls for further study in this area (Skogdalen & Vinnem, 2011).

Table 2: Levels of Quantitative Risk Assessment based on Human and Organizational Factor Inclusion (Skogdalen & Vinnem, 2011)

Level of QRA	Requirement
Level 4	QRA is an integrated part of the safety and risk assessment program; it is known and accepted at all levels of organization and is combined with risk indicators to reveal the status of safety barriers.
Level 3	- Systematic collection of data related to HOFs - QRA models adjusted according to findings from HOFs - Identifies causes of errors
Level 2	- Explains the importance of HOFs - Human error is calculated separately - Interview done with crew and results published, but models and calculations are not adjusted
Level 1	- Solely based on technical analysis, no attention to HOFs

The failure to implement HOFs in QRA was echoed in Skogdalen *et al.* (Skogdalen et al., 2012).

In this study, 15 QRAs from North Sea were analyzed and the authors found that the Risk Influencing Factors (RIFs) were not covered in the conceptual phase of the well planning. The Macondo blowout incident was presented as a case study to emphasize the importance of incorporating HOFs in QRA study since most of the findings associated with the incident were related to HOFs, *e.g.*, communication, competence, procedures, management, working practice (Skogdalen et al., 2012).

One model attempting to include HOF was proposed by Embrey *et al.* (Embrey, 1992). This model was designed to factor the influence of management and organizational factors into risk assessment. The model, referred to as MACHINE—an abbreviation for Model of Incident Causation using Hierarchical Influence NEtwork—can address both qualitative and quantitative contributions toward risk of the management and organizational factors. This tool can be used as an audit and monitoring tool for management and organizational factors as well as a tool for predicting failure probabilities for both human factors and hardware (Embrey, 1992). To demonstrate the application of the model to probabilistic safety assessment, a simplified analysis for an incident was conducted and found that assigning probability data without empirical data made the model difficult to apply effectively.

The general Probabilistic Risk Analysis (PRA) models are used to tie the system failure probabilities with the probabilities of initiating events, human errors, and component failure. Sometimes management errors occur due to various organizational factors such as failure to monitor situations or time pressures. Furthermore, these errors may increase failure probability of initiating events or decrease system capacity. There has been some effort to include the possibility of management errors into the PRA. Pate-Cornell introduced some organizational aspects that can be related to the probability of failure of equipment. The study identified some root causes of HOF aspects, such as time pressure, missed signals of deterioration, conflicts between productivity and safety, failure to transfer knowledge and learning, and uncertainties of decision. They also recognized the element of subjectivity associated with probability calculation of technical and human performance and thus the difficulty of integrating these variables into QRA models (Pate-Cornell, 2010).

The case study of the Macondo Incident was used by Norazahar *et al.* to analyze the framework of emergency readiness and evacuation procedure (Norazahar, Khan, Veitch, & MacKinnon, 2014). For this purpose, four layers of protection were identified, namely equipment, procedure, personnel, and procedure. Their study explored the contribution of HOFs in the emergency preparedness in each of these layers. The study identified several HOFs responsible for the Macondo well blowout including lack of training and emergency drills, poor communication, and poor preparedness for emergency. Although the study results are qualitative, the study proposed the application of a Bayesian network as future work for the added benefit of estimation of success probability of evacuation (Norazahar et al., 2014).

In order to assess the effect of Human and Organizational Errors, specifically on the life-cycle reliability analysis and quality assurance of offshore installation, Bea *et al*. developed a formulation and a software application named SYRAS (System Risk Assessment Software) (Bea, 1999; Bea, 2002). In this study, a qualitative process named Quality Management Assessment System (QMAS) was employed to assist the team in examining important parts of an offshore system during the lifecycle and SYRAS was used as a quantitative tool to aid managers and engineers in identifying major tasks and associated failure probabilities and thus in assessing risk. QMAS and SYRAS both have been applied to a wide variety of offshore structures, including offshore drilling and production platforms, ships (including marine terminals), and pipelines. For example, in one government-industry joint project, the life-cycle reliability of four structures had

been compared in terms of robustness against HOF using these tools. The project demonstrated the importance of the current assessment in providing insight into performance of the installation and therefore recommended application of the reliability assessment method in the initial and detailed design phase of a project (Bea, 1999; Bea, 2002).

Bayesian Network: A Bayesian Network (BN) is a graphical representation of the dependencies among a set of variables under uncertainty with directed arcs connecting the node variables. Each node is associated with a conditional probability table or node probability table. BN has been a well-known tool for reliability assessment for both predictive and forward analysis. For both predictive and forward analysis, the risk is calculated based on the probability of occurrence of the nodes and conditional dependence of these nodes.

In order to account for the HOFs as well as technical aspects of design, construction, and operation in offshore O&G Wang *et al.* built a "Swiss Cheese" model using a BN (Wang, Xie, Habibullah, & Ng, 2011a). According to this model, multiple risk factors can be identified for offshore operation and then Reason's "Swiss cheese" model can be used to form a generic offshore safety assessment framework. Later, the BN was tailored to fit into the framework to construct a causal-relationship model (Ren, Jenkinson, Wang, Xu, & Yang, 2008). The proposed framework used a five-level-structure model including consequence, incident, trigger event, and root cause levels to address hidden failures within the causal sequence. This model requires expert judgment data as input and can be used to calculate likelihood values for the occurrence of failure. Further, BN interference may help monitor changes in safety situation. A case study has been performed on risk assessment for the collision risk due to HOFs between a Floating Production, Storage and Offloading (FPSO) unit and regular vessels. It was found that the combined application of Swiss Cheese Model and BN is possible for offshore safety assessment (Ren et al., 2008).

Røed *et al.* developed a hybrid causal logic (HCL) model to incorporate HOFs that was built based on traditional risk assessment tools and was combined with Bayesian Belief Networks (Røed, Mosleh, Vinnem, & Aven, 2009). This study reviewed the framework and discussed its potential applicability in the offshore O&G industry (Røed et al., 2009). The HCL method was employed to determine the failure case for a case study of fire in a drier unit in the offshore O&G industry (Wang et al., 2011a). The study demonstrated that HCL is an effective method to determine failure cause and to show non-deterministic cause-and-effect relationship among system variables.

In a study by Cai *et al.*, BN and pseudo fault-tree analysis were employed to perform QRA for offshore blowout incidents (Cai et al., 2013). A typical fault tree shows the interrelationship between the potential critical event and the causes with a binary restriction of the event either happening or not happening. The concept of pseudo fault tree has been introduced to account for the intermediate option which is essential for reliability analysis for human factors (Cai et al., 2013) In this study, three types of errors, namely Individual, Organizational, and Group Factors, were identified and classified as Human Factor Barrier Failure (HFBF). Each type of error has been reported to contribute differently to the overall HFBF and these error barrier failures are depicted using a pseudo fault tree. Application of a dynamic Bayesian Network to this fault tree has been validated via sensitivity analysis which is essentially a way to see how sensitive the result or conclusion is with the evidence used to compute the posterior probabilities (Jensen, Aldenryd, & Jensen, 2005).

To incorporate the effect of HOF, Wang *et al.* developed a probability analysis model that converted Fault Tree (FT) Analyses into BN and was used to model offshore fires (Wang, Xie,

Ng, & Habibullah, 2011b). FT has been used primarily as a tool for identifying factors that contribute in a fire scenario. The contributing factors were then employed to construct the BN model and the latter was extended to incorporate the effect of HOFs. This BN model provided a quantitative relationship among the event nodes and a better estimate of the occurrence probability for the top event. In order to validate the model, four offshore fire scenarios were used as example case study. By using the method developed in this study, the authors were able to identify the most probable cause(s) of failure. They emphasized the importance of further research on how to incorporate the entire offshore O&G production system in the analysis since it would be too complicated to present in a single FT (Wang et al., 2011b).

BN was employed in another study where the Human Performance Shaping Factors (PSFs) were used to represent the relationship between human elements and related actions. For this study, PSFs were identified at each phase of the hierarchy, and then a BN was built based on the PSFs. This model was then used to calculate the likelihood of task failure and corresponding Human Error Probability (HEP). The whole calculation was demonstrated for an offshore emergency evacuation scenario analysis (Musharraf et al., 2013) and after comparing the solution with an analytical approach, the study showed the proposed method's utility on estimating human error probability. Moreover, the proposed methodology is flexible enough to accommodate dynamic changes in the BN.

Human Reliability Analysis: Human Reliability Assessment (HRA) is a hybrid tool, arising from the disciplines of engineering and reliability on one hand and psychology and ergonomics on the other hand. The former discipline requires HEPs to fit into the logical mathematical framework of Probabilistic Safety Analysis (PSA) and the latter urges more detailed and theoretically valid modeling of the complexity of the human worker and human performance (Wilson & Corlett, 2005).

A complete HRA process will identify the types of error in a system, predict ways of those errors occurring, and provide direction on how to reduce the probabilities of such human error (Kirwan, 1987). HRA originated from the mixture of engineering and the reliability discipline along with ergonomics and psychology. While the ergonomics and psychological discipline asks for validation of theoretical model regarding the complex interaction of human worker and performance, the engineering and reliability aspect requires the HEPs fit into the mathematical framework of PSA (Wilson & Corlett, 2005). After the Three Mile Island incident in 1979, this tool has been widely used for the prediction and prevention of large scale incidents (Kirwan, 1987). For a relative comparison between hardware or equipment and human components of risk, this is a useful tool and the human error data required by HRA can be both quantitative and qualitative. From that perspective, HRA can be considered as a part of QRA. However, human reliability analysis itself is a broad topic and has numerous components.

Kirwan *et al.* worked primarily on the quantification of the probabilities or likelihood of human error (Kirwan, 1996). More specifically, the researchers performed Hierarchical Task Analysis (HTA) for tasks associated with lifeboat evacuation process and generated HEP. Their data collection methodology included visual observation, expert judgment session, and incident investigation report study. While the study is not comprehensive enough to enlist all possible HEPs, it focused more on the methodology development and data collection for such studies (Basra & Kirwan, 1998). As future work, they suggested the development of more detailed risk or human reliability assessments to account for the error prioritization and consideration of an error recovery factor.

Bercha *et al.* developed a computer model to investigate human performance under extreme

conditions during emergency evacuation in an Arctic environment as a part of Escape, Evacuation and Rescue (EER) program (Bercha, Brooks, & Leafloor, 2003). In this method, risk analysis for identifying failure and simulation for modeling time sequence of various operations was done simultaneously to understand the interaction of both. Though human performance is an important parameter for a successful EER program, the study revealed that the technological and mechanical shortcomings of the Arctic had greater contribution compared to human failure.

Skalle *et al.* developed an improved evaluation methodology based on the hierarchical ontology of oil-well drilling process and their methodology uses both technical error and human error to point out failure probabilities. The technical errors were related to drilling processes whereas the human errors were based on organizational failure. This model was able to predict failure, and experience and expert judgment were used to validate the model calculation. However, for better validation of the model, more testing has to be performed before real industry application (Skalle, Aamodt, & Laumann, 2014).

Okoh introduced the concept of optimized maintenance grouping. Maintenance grouping is done in order to ensure high cost effectiveness through the optimization of maintenance activities, and it can be done in conjunction with the benefits available from risk reduction methods. This study demonstrated the potential of the maintenance grouping strategy and subsequent risk reduced through an example of a hypothetical riser system. In this demonstration they were able to calculate the least possible cost associated with maintenance and also the optimum frequency of maintenance (Okoh, 2015).

Gordon *et al.* developed the Human Factor Investigation Tool (HFIT) for incident analysis (Gordon, Flin, & Mearns, 2005). The tool requires data on action errors taking place before the incident, thought processes leading to the incident, mechanisms for error recovery, and root causes. The application of HFIT is very theoretical and does not include any human error probability values. However, based on the result of a case study of offshore incident scenario, the researchers concluded that HFIT is a useful tool for providing remedial action for small-scale incident investigation.

For estimating the HEPs associated with the workers, a cognitively based Human Reliability Analysis technique had been developed and employed for nuclear power plants. The tool known as Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) identified eight Performance Shaping Factors (PSFs), namely available time, stress and stressors, complexity, experience and training, procedures, ergonomics and human-machine interaction, fitness for duty, and work processes. The PSFs had been identified based on a review of cognitive activities and data available from HRA in the THERP (Technique for Human Error Rate Prediction) method. The intent was to develop a defensible method that would consider all factors that may influence performance (Blackman, Gertman, & Boring, 2008). Indeed the Norwegian Petroleum industry employed the SPAR-H technique as a part of major incident risk analysis (Gould, Ringstad, & van de Merwe, 2012). The paper describes in brief a strategy for integration of HRA along with preliminary results. It also presents the similarities and dissimilarities between the nuclear and offshore oil industries in terms of the application of the HRA tools. To enhance the consistency of SPAR-H analysis, Laumann *et al.* conducted a review of PSFs and interviewed consultants experienced with SPAR-H analysis. The study identified that there is difficulty in choosing the appropriate level due to unclear and overlapping definitions of PSFs and SPAR-H analysis. Based on this observation, some new definition of PSFs and more varied levels and multipliers to the analysis were suggested (Laumann & Rasmussen, 2016).

Deacon *et al.* developed a risk assessment tool termed ARAMIS (Incidental Risk Assessment

Methodology for IndustrieS) for evaluating risk associated with human error during offshore emergency musters. The study identified difficulty associated with obtaining empirical data for calculating the consequence of failure in the muster process. Therefore, they used data from past offshore incidents and validated the results of the Ocean Odyssey incident using the ARAMIS method to evaluate safety barriers (Deacon, Amyotte, & Khan, 2010).

Dimattia *et al.* also conducted research on an offshore O&G emergency muster process. They recognized the lack of a human error database for offshore platform muster and used the Success Likelihood Index Methodology (SLIM), a method utilizing expert judgment to predict human error probabilities. This method included six PSFs: stress, complexity, experience, training, event, and atmospheric factors. These factors were used to calculate the probability of successful muster processes (DiMattia, Khan, & Amyotte, 2005). Based on the SLIM modeling approach, Khan *et al.* introduced the Human Error Probability Index (HEPI) that was also applied to the offshore muster process (Khan, Amyotte, & DiMattia, 2006). HEPI aids in risk estimation by calculating human error probabilities and their consequences for the muster process. As suggested by the authors, the HEPI tool can be enhanced by developing a good human error database (Khan et al., 2006).

Gaps:
More validated Quantitative Risk Analysis (QRA) efforts are needed before they can be effectively leveraged in O&G: Previously, QRA had been limited by the fact that it does not incorporate Human and Organizational Factors (HOF) and this review illustrates that several efforts have been made at incorporating HOF into QRA. However, most, if not all of these efforts have not resolved the issues of subjectivity associated with probability calculation of technical and human performance and the difficulty of integrating these variables into QRA models (Pate-Cornell, 2010), nor have they validated their models against rig performance. There is also lack of a knowledge regarding how to leverage computational cognitive models on human performance that can very effectively predict human performance (e.g., Card, Newell, & Moran, 1983; Byrne, 2001; Kieras, 2016). Indeed some efforts have already been made towards this in the construction and nuclear industry (Boring, Joe, & Mandelli, 2015; Fang, Zhao, & Zhang, 2016)

Research needs to be conducted on how to organize and present the results of QRA analyses so they can be leveraged effectively: For instance, to incorporate the effect of HOF, Wang *et al.* developed a probability analysis model that converted FT Analyses into BN and was used to model offshore fires. However, they indicated the need for further research on how to incorporate the entire offshore O&G production system in the analysis since it would be too complicated to present in a single FT (Wang et al., 2011b). Further, Kirwan *et al.* worked primarily on the quantification of the probabilities or likelihood of human error (Kirwan, 1996). They suggested development of more detailed risk or human reliability assessments to account for error prioritization and consideration of an error recovery factor. With the current PSFs and SPAR-H analysis methods, this is difficult due to the unclear and overlapping definitions of error in each of these methods. Based on this observation, some new definition of PSFs and more varied levels and multipliers to the analysis have been suggested by Laumann & Rasmussen (Laumann & Rasmussen, 2016).

14. CREW RESOURCE MANAGEMENT
The importance of non-technical skills for safety and efficient operations has been a recognized concept in many years in industries such as aviation, military, and nuclear, and it is beginning to become more widely accepted in the medical field as well (Flin, 1995; Salas, Wilson, Burke, & Wightman, 2006). The O&G industry has experienced catastrophic incidents from Piper Alpha to

more recently Deepwater Horizon (Macondo) specifically related to non-technical skills. Incident analysis and psychological research have helped to determine the importance of understanding how workers' perceptions and motivations can augment operational safety and performance (O'Connor & Flin, 2003; OGP, 2014a, 2014b). A shift has occurred in the O&G industry to recognize the importance of developing training programs focused on the application and development of non-technical skills, and one method of doing this is Crew Resource Management (CRM)(Flin, O'Connor, & Mearns, 2002).

CRM is used for reducing the likelihood of incidents and increasing the efficiency of operations through teamwork by supporting cognitive and social skills that complement workers' technical skills (Flin, 1995), such as interpersonal communications, decision-making, SA, teamwork, and leadership (Flin et al., 2002; O'Connor & Flin, 2003). CRM training was initially implemented in aviation. Due to its success, other high-risk domains began implementing similar programs throughout their workforce (Salas et al., 2006). While CRM training was initially designed to mitigate operational errors and improve emergency response in aviation crews, companies using this method have also reported significant benefits for normal operational performance (Flin et al., 2002; O'Connor & Flin, 2003). These programs are being applied to the offshore O&G industry in anticipation of improving safety and increasing productivity in a variety of tasks where teamwork is essential (Flin, 1995).

In 2003, O'Connor & Flin were tasked with developing, implementing, and evaluating a prototype of a CRM training program specifically aimed at offshore O&G production teams. Overall results proved that the CRM training had beneficial qualities. Workers reported having positive reactions towards the program and a slight change in attitude towards decision-making and personal limitations such as stress and fatigue. On the other hand, there was no increase in human factors knowledge following training. Another important finding from the study was the evaluation measures needed to be more sensitive to determine the impact of CRM training programs on operational safety performance in these high-risk environments (O'Connor & Flin, 2003).

There are two main methods for assessing the efficiency and effectiveness of CRM training program: observing and rating workers' performance while completing a task, and using an attitude survey. These methods yield different types of results and both help to determine if the worker was able to transfer knowledge and improve performance due to their training (O'Connor, O'Dea & Flin, 2008). Behavioral assessment tools are better able to evaluate performance in terms of whether or not observable, non-technical skills trained during the CRM training are being used in the workplace. Attitude surveys are a means of measuring whether the workers learned and retained the material that presented to them (O'Connor *et al.*, 2008). Regardless of which evaluation tool is used, these rating systems serve as methods for reliably and objectively measuring the effectiveness of CRM training programs (Flin, O'Connor, & Crichton, 2008).

Salas *et al.* evaluated 28 CRM training programs for effectiveness in different domains such as aviation, maritime, nuclear power, medicine, and offshore O&G (Salas et al., 2006). They concluded that CRM training programs conducted in either real or simulated environments yield positive reactions, enhanced learning, and desired behavioral changes (Salas et al., 2006). However, the impact of CRM training programs on actual learning, behavioral changes, and competencies varied across their respective domains. Thirteen of the 28 studies, including two studies from O&G, found evidence showing trainees had positive reactions towards the training (*e.g.*, liked it, felt it would be helpful). Moreover, eight of the 28 studies identified domains where the training led to desired changes in attitudes (*e.g.*, aviation maintenance, air traffic control,

medical, maritime, nuclear, and offshore O&G). Specifically, for the O&G domain, there has been evidence that trainees had a positive change in attitudes towards decision-making and personal limitations. However, results showed that behavioral changes were more likely to be observed in military, maritime, nuclear, and medical domains (Fonne & Fredricksen, 1995; Harrington & Kello, 1992; and Morey *et al.*, 2002 as cited in Salas et al., 2006). Aviation maintenance was the only domain with findings that showed an increase in assertiveness, coordination, decision-making, and stress management (Taylor, 1998, 2000 as cited in Salas et al., 2006). Overall, for the O&G domain, CRM training programs have produced similar results as in other high-risk industries in terms of learning content. However, behavioral changes were inconclusive at this point as studies involving offshore O&G have yet to evaluate behavioral data.

The variability of these results suggest a need to evaluate CRM training programs at multiple levels, and not rush to assess the impact of these programs by a snapshot at a single level for both the worker and the organization (Salas et al., 2006). These multiple levels should be based on Kirkpatrick's typology of the four levels of learning evaluation model (*i.e.*, reaction, learning, behavior, and results) (Kirkpatrick, 1975). Regardless of any positive perceived impact conveyed by training, there is a lack of empirical evidence showing any degree of certainty that CRM training contributes to increased safety in the workplace. Furthermore, in order to determine the impact of these programs several tools need to be implemented. These tools might include providing a mandate, affording access to facilities and trainees, and going beyond the traditional safety measures of incident rates (Salas et al., 2006).

In 2014, the International Association of Oil & Gas Producers (IOGP) published OGP Reports 501 and 502. These reports are the first industry-level guidelines specifically addressing human factors, the lack of non-technical skills, and how to effectively implement CRM training programs. With the publication of Report 502: Guidelines for implementing Well Operations Crew Resource Management Training," IOGP is working to advance efforts in making sure the O&G industry implements CRM training programs as best practice to reduce the occurrence of or mitigate the effects of major well incidents (OGP, 2014a, 2014b; Salas et al., 2006).

Gaps:
Measurement methods customized for O&G need to be developed and validated to allow the validation of CRM efforts: The development of these types of training programs should be based on needs analysis and be customized to support workers in specific domains, for instance, offshore drilling and production industries (Flin et al., 2002). Although CRM shows remarkable promise for reducing the likelihood of incidents and improving SA, there is a lack of empirical evidence showing the impact of CRM training for the O&G industry as most of the current evidence has been exclusively on participants' self-reported reactions and attitudes about the training program. For example, O'Connor & Flin developed and delivered CRM training based specifically on offshore control room environments (O'Connor & Flin, 2003). The training resulted in the successful determination of workers' affective feelings towards the program (*i.e.,* positive or negative), as well as the utility of the program (*i.e.,* was the program useful or valued by workers). However, the research team discovered there was a need for more sensitive measures for determining the effectiveness of CRM training on operational safety performance. Roberts and Flin (2016) have begun using behavioral ratings of drillers for just this effort and have found some promising results. However, this is a nascent approach in O&G and further research is required to validate and refine it.

Simulations should be leveraged to test effectiveness of CRM methods: Developing effective methods to evaluate workers' attitudes, skills, and behaviors is essential in establishing whether the elements of CRM training are creating desired outcomes. However, these evaluation methods

are difficult to do in the field. Therefore, to assess whether or not CRM training can effectively produce results that promote the transference of desired behaviors during routine operations, it may in fact be more effective to do experimental evaluations in simulation-based training environments where workers' skills and behaviors can be observed (Flin & Martin, 2001; Mearns et al., 2001). There has been minimal empirical evidence regarding simulation-based training and whether or not workers can successfully transfer knowledge gained during training into desirable changes in behaviors. Salas *et al.* reviewed several studies that exclusively examined changes in behavior through simulation observations (Salas et al., 2006). Four of the studies reported having mixed results, where the transfer of some positive skills such as communication were observed while other skills were not. An additional four studies reported only positive outcomes. Future research is needed to examine possible reasons for inconsistencies in the above results, as well as determining the effectiveness of simulation-based training for both individual workers and teams, specifically targeting the offshore O&G environment.

OVERALL GAPS IN CURRENT EFFORTS

One fundamental shortcoming of existing research. As in so many fields, most of the data on disasters and other safety challenges or interruptions of operations come from naturalistic study, are simply observational or at best correlational, and rely solely on self-report of their major outcome variables (*e.g.*, safety behavior). Although these studies are undeniably important and many of them are groundbreaking, by themselves they are not sufficient to identify the most effective methods of creating safe operating environments for offshore drilling. The reason for this dearth of experimental research is likely due the fact that it is difficult, for ethical reasons, to set up an experiment—the only research method that would afford attribution of cause-and-effect—in such a hazardous environment, whereby the chances of a disaster are increased. Thus, the well-intentioned O&G decision maker who wishes to steep his or her decisions regarding rig designs, safety programs, and training in research is forced to make inferential leaps. What design changes truly led to that improved safety record? What specific combination of UI and workflow design features conspired to spawn that disaster? However, there are ethical methods of conducting empirical studies that can and should be conducted to identify the causal relationships between the variables identified in the sections above. For instance, researchers and businesses could use pre-post designs where they compare the outcome of interest (number of safety incidents, effectiveness of performance, *etc.*) before and after the intervention (CRM, interface redesign, alarm management strategy implementation, *etc.*). Further, there are numerous facilities across the globe where specific scenarios can be simulated with remarkably high fidelity. These facilities are typically built and used for training but can be used very effectively to determine the effectiveness of many of the interventions and programs discussed above.

In each of the human factors topics discussed above, we identified gaps in the current research and potential future directions for that research in offshore drilling. We have further identified the following topics that we believe are good candidates for "next steps" in human factors research to facilitate drilling safety. In our summary of the extant, applicable research findings, above, we often found ourselves saying, "More research needs to be done." This is a common lament among academics. In this case, we considered the apparent gaps in our awareness of the important human performance variables, the important human-machine interaction variables, and the important team/environment variables to derive these four areas for future research that we believe will be fruitful.

1. PERCEPTUAL VS. COGNITIVE-BASED DECISION MAKING.

While Endsley's aforementioned perception versus comprehension SA errors addressed the distinction between perceiving and actually *understanding* information in the environment, here

we are concerned with the level of human information processing required to *make a decision* once all of the information is available. Cognitive engineering emphasizes the design and development of complex systems taking into account certain aspects of human behavior. Given the extraordinary amount of information that certain workers on a drilling rig need to process to make effective decisions, the importance of this approach cannot be understated. For instance, the driller needs to maintain an awareness of the current status of the drilling floor (*e.g.*, who is on the floor and what they are doing), monitor the well for influx or loss of fluid; use instrumentation to know the conditions of the bottomhole, wellbore, and drillstring conditions, and use this information to make judgments about whether and if so what corrective actions need to be taken in the event of an adverse event (Reinhold & Close, 1997). The cognitive engineering approach leads to building advanced information systems that aid in problem solving and decision making with effective and efficient cognitive effort. Judgment and the decision making process are higher order processes than memory and attention for effective problem solving under high workload conditions. This means that one cannot make good judgments and decisions without remembering essential information or attending to critical aspects of the environment.

Harbour & Hill offer a model of input detection, input understanding, action selection, action planning, and action execution (Harbour & Hill, 1990). Similarly, one view of cognitive processing offers four component areas: judgment, decision-making, memory, and attention (Andriole & Adelman, 1995). Thus, effective processes of perception and pattern recognition on displays allow improvement of performance and reduction of the cognitive responsibilities (Bennett & Flach, 1992). For example, we know that recognition is typically much easier than recall – that is, human beings can recognize a bit of information (*e.g.*, a menu item such as "erase") more readily than they can recall it from long-term memory (see, *e.g.*, (Johansen, 2014). Therefore, user interfaces that require recall (*e.g.*, command-line interfaces) are harder to learn and use and more subject to error than those that demand recognition (*e.g.*, menu systems).

So imagine a continuum of decisions, based on ever more complex human information processing. Imagine a decision that is based only on sensory information: "Push that button if you see a light on your computer display." Any spot of light—any size, any shape, any intensity, any location—is the trigger for the action. Moving up the human-information processing chain, imagine a decision based on perceptual information. Instead of pushing a button in response to any light, the correct action is to push a button only in response to a blue light. So if a green light comes on, or a red light, or a yellow light, push no button. Rather than a simple sensation, a particular perception is the cue to act. What if cognition is needed? What if the human must do some thinking about that blue light? Perhaps the rule is to push the button if a blue light comes on but only if it is a circle and not a square. Or only if it appears on the left half of the display. Or only if the two numbers that are also shown on the screen add to an even number? Such cognition-based decisions take longer and are more error prone than are perception-based decisions.

So, while this in not a new concept, see (Bias, Nixon, He, & Kim, 2014), one thread of research that is likely to be fruitful is the identification of user interface components (read-outs, figures, graphs) that allow workers to make decisions based on lower-order, fundamental human information processing capabilities rather than demanding more cognitively expensive capabilities. To the extent that offshore drilling workers can make decisions more quickly and perform actions more accurately, more errors will be identified and avoided or corrected.

2. *INSTANTIATING SUPER WORKERS' WISDOM*
Earlier we cited De Cort's address of SA for young versus experienced offshore workers (De

Cort, 2015). As in any field involving technology or not, there is going to be a range of excellence of skills among people who are performing the same tasks. That is, some baseball pitchers are better than others, and likewise with electricians, teachers, or drilling platform workers.

Commonly, the experienced worker is better than the beginner, owing to his or her knowledge learned from experience. One example would be in the ability to spot trends. In our earlier work with refinery control rooms (Bias et al., 2014) it was reinforced for us that there are excellent, experienced "super" workers who can spot trends, and thus can anticipate and interrupt a would-be alarm state before it triggers the alarm. The worker notes that the value of this variable (some temperature or pressure, say) is X and rising, and this other value is Y and descending at a particular rate, and he or she knows that the probability of an alarm condition is elevated. Then that worker intercedes, before the alarm, thereby preventing the out-of-range condition, possibly preventing subsequent down time. How can we capture that "super worker's" knowledge? How can we build that knowledge into the rig control software? How might we identify and present this trend information in a way that would allow a new or typically mediocre worker to perform at the same level as the super worker? Ultimately, how might we build this knowledge into artificial intelligence systems that take the element of human error out of the equation? This would be a research thread that would pay quick dividends.

3.   VIGILANCE

So much of the worker's job is a vigilance task (see the "lapses of attention" per Sneddon *et al.* (Sneddon et al., 2006a). Our experience in control rooms has revealed that actually this is a two-part issue. The most obvious problem is remaining vigilant for the exceedingly rare event. As technology inexorably improves—as we assume the context of a "high-reliability industry"—the number of errors declines. Thus the worker may be in the position of trying to remain vigilant for rarer and rarer events. How do we design systems to help the worker maintain attention and focus? Might there be value in insinuating fake error conditions routinely (though not at routine intervals) throughout a shift? If so, what would be the optimum rate of created, fake problems? How can this be put into practice in a way that doesn't hurt teamwork at the site? Might there be knowledge generalizable from "serious gaming" to apply to drilling control programs?

4.   STRESSED PERFORMANCE TESTING

Recall the discussions relating to stress and fatigue and the importance of understanding their effects on performance. It is difficult to gain approval from the "ethics committee," or the IRB (Institutional Review Board), to simulate a life-threatening condition to see how people perform in it. Or, it is difficult to do likewise in order to conduct some A|B testing (a test of two competing designs), to see whether this or that GUI better supports the avoidance of a disaster. Earlier we noted the "lament" of O'Connor & Flin of the low incident rate offshore (not providing a robust testing environment) (O'Connor & Flin, 2003). Well, there are simulations environments available (e.g., Texas A&M Engineering Extension Services Fire School and Disaster City) where this kind of work can be done. These simulation environments are typically built to train for emergency response at all levels, and can usually support research and design of excellent systems in which people are performing under unusual levels of stress (*e.g.*, firefighting, EMS). This type of resource could be of tremendous value to researchers for testing emerging GUIs and other system designs (workflows, team dynamics).

5.   RETURN ON INVESTMENT

Any application and implementation of HF will require clearly addressing the business case for HF and developing cost effective methods for retrofitting the existing facilities. These types of

return on investment (ROI) for HF will require academic and industry research partnerships to gather information from offshore workers regarding impacts of the risks identified, *i.e.*, collaborative empirical research. Of course all drilling companies concern themselves with ROI (Mearns, Whitaker, Flin, Gordon, & O'Connor, 2000). In recent years there has been a move in the human factors/usability field toward identifying the ROI for specific bits of human factors support *e.g.* (Bias & Mayhew, 2005; Mayhew & Bias, 1994). When it comes to safety, the "return" can mean revenue, but it also can mean avoiding disasters, saving lives, preventing injuries, and avoiding bad public relations events. A valuable research thread could be the identification of which human factors evaluation methods, applied at which specific points in the drilling system design, yield the best return for the money invested in the conduct of the methods.

6. *KEY PERFORMANCE INDICATORS*
Finally, for any business to know whether or not their systems and programs are making meaningful progress toward successfully integrating HF/E, the leaders of that business—indeed the leaders of the businesses in the industry—need to develop key performance indicators (KPIs) that can be measured and tracked to show improvement (or lack thereof). In 2010, the Energy Institute generated a report on Human Factors performance indicators for the energy industries. It was focused primarily on the mid- and down-stream aspects of the industry (Institute, 2010). Nevertheless, the fundamentals and challenges of identifying and measuring HF performance indicators for these domains are similar for many upstream environments including offshore. The primary challenge is clearly stated in this document as: How to identify the best HF KPIs to measure and track for *each company* and *each facility*. They go on to offer possible processes for identifying processes for identifying HF KPIs and a list of possible KPIs are given such as: procedures being technically correct and safety critical staff assessed to be competent in their role. These processes and constructs are logical and have face validity based on the tenets of HF science and practice. However, because they are administrative controls, these example indicators focus on the least effective methods of safeguarding from hazards that HFE methodologies and principles can offer. Thus are more likely lagging than leading indicators of effective use of HF.

One of the challenges of developing HF KPIs is the high amount of effort required to generate a KPI with sufficient specificity for measurement. Some companies (*e.g.*, Definitions, Health and Wellness and British Petroleum HSE) have begun to establish some KPIs around HF and safety but this is not wide spread. More effort needs to be focused on establishing meaningful and measureable KPIs that can facilitate the integration of HF principles and practices into the O&G business practices.

DISCUSSION
As promised, this paper presents a summary of the literature investigating human factors issues in the O&G industry and how (and to what extent) the findings from those investigations are currently being incorporated into O&G operations offshore. Further, we articulate gaps in the knowledge and application for the topics identified in these reviews. From these reviews, three main themes can be articulated regarding needed focus for the O&G industry in Human Factors to facilitate efficient, effective, and safe work: the need to identify the specific elements of the *human-machine interaction* that will support this type of work; the need to utilize modeling and management systems to allow industries to *most effectively leverage knowledge regarding human factors* into the process of human systems integration; and finally, the need to create the *environment* for this type of work to occur.

Offshore drilling and production rigs contain hundreds of computing systems to operate systems such as drilling, generators, remotely operated vehicles, *etc*. Further, there are multiple aspects of

rig operations such as crane operation, casing and string management, mechanical repairs, *etc.*, that may be supported by computing systems but still have primarily humans doing the basic work. Thus, simply identifying each instance of human-machine interactions can be non-trivial—let alone optimizing those thousands of interactions for the humans who are supposed to use them. Further, given that a drilling rig is a complex sociotechnical system (STS) where all systems impact all other systems, designers cannot simply optimize the interactions between each human and the technology each of those humans use, they have to optimize the interactions of the entire system—how those technologies and people interact and design systems that support those interactions as well. This is referred to as Human Systems Integration and is necessary for these types of complex system. Norman has recently discussed some design processes for complex STS and although the specific example is couched in the medical domain, many of the issues can be easily generalized to O&G (Norman & Stappers, in press). For instance, he discusses how ineffective methods for bringing patients into the hospital can lead to routine, but lifesaving, procedures not being done because the duty nurse did not know that a new patient was on the floor. Whether the procedure was not followed, not set up correctly, or the method for doing the procedure was confusing and thus led to input errors will not matter to the patient who does not get the appropriate care. O&G has effective modeling and management systems for building phenomenally complex technology. Those systems now need to be adjusted with collaborated efforts to include Human Factors and Human Systems Integration.

Some of the research regarding the environment is more mature than others in O&G. For instance, the importance of safety culture/climate research and its applications have been known since 1998. However, the causal mechanisms between safety culture/climate, safety behavior, and incidents have not been clearly established. Further, the reviews presented here suggest that other variables may remarkably influence the environment and safety culture/climate, such as training (*i.e.,* CRM), stress, and risk perception. One of the most profound and indeed disturbing findings regarding the review of the safety culture/climate literature is that this is the content domain of human factors that the offshore O&G industry seems to have the longest history with and yet it is the issue identified as a primary cause of the Macondo incident in 2010 where 11 lives were lost, clearly indicating that knowledge of the problem within the offshore O&G industry does not indicate resolution of that problem. This paper has presented that there are risks in O&G when human factors is not included in the design, construction, operation, and management of these systems. The mitigations of these risks are not easy or obvious but the paths to identifying these mitigations methods are obvious. They are illustrated in the successful programs reviewed here—interdisciplinary industry/academic partnerships focused on solving industry problems with scientifically valid, empirical findings and solutions that can be quickly deployed. Possibly the most important work for the O&G industry then is to decide what are the primary roadblocks for implementing good Human Factors information and effective tools that have been available. It is only then that the good work of those authors reviewed here can be fully leveraged.

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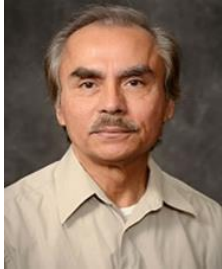
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The Ocean Energy Safety Institute (OESI) is a collaborative initiative between the Texas A&M Engineering Experiment Station's (TEES) Mary Kay O'Connor Process Safety Center, partnering with Texas A&M University, University of Texas and University of Houston. The institute provides a forum for dialogue, shared learning and cooperative research among academia, government, industry, and other non-governmental organizations, in offshore energy-related technologies and activities that ensure safe and environmentally responsible offshore operations. While there have been efforts to identify scientific and technological gaps and to recommend improvement of drilling and production equipment, practices and regulation, the OESI will strive to coordinate and focus these products. Initial funding of the Institute came from the Department of the Interior and the Bureau of Safety and Environmental Enforcement (BSEE).

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