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Application of Inherent Safety to Maintenance-related Major Accident Prevention on Offshore Installations

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Organizations associated with the handling, processing or storage of hazardous substances, have the potential for major accidents. The offshore industry, for example, handles dangerous substances like crude oil and gas.
The operations of the offshore industry are usually quite complex and it is a common practice to deploy and maintain multiple safety barriers. However, deficiencies in maintenance have been significant contributors to the occurrence of major accidents. Procedural, passive and active risk reduction strategies are often relied upon, but these have yet to achieve optimal risk reduction due to inadequacies in procedures or the degradable, physical safety systems. Inherent safety, which can be considered to be a subset of green chemistry and engineering, is known to be a more robust and cost-effective risk reduction option and applicable at any stage during design or operation. Based on this knowledge, we intend to exploit the versatility of the principles of inherent safety for the purpose of achieving improved risk reduction in relation to maintenance.
The main objective of this paper is to investigate how inherent safety can contribute to maintenance-related, major accident risk reduction on offshore installations. The paper builds on a review of literature related to risk reduction strategies, inherent safety and the maintenance work process.

1. Introduction

The operations of the offshore industry are usually quite complex in the presence of hazards such as oil and gas. So, it is a practice to deploy and maintain multiple safety barriers to prevent the associated major accidents. However, deficiencies in maintenance have been significant contributors to the occurrence of major accidents (Okoh and Haugen, 2013). Procedural, passive and active risk reduction strategies are often relied upon, but these have yet to achieve optimal risk reduction due to inadequacies in procedures or the degradable, physical safety systems. Inherent safety, which can be considered to be a subset of green chemistry and engineering (Hendershot, 2006), is known to be a more robust and cost-effective risk reduction option applicable at any stage in design or operation (Khan and Amyotte, 2002).
Several major accidents have occurred over the last three decades with devastating consequences and these have resulted in new realizations, including implications for inherent safety. Some of these have been adapted through regulatory changes, new standards and new methods that improve safety. The Bhopal gas tragedy in 1984 and Texas City Refinery Explosion in 2005 are examples of major accidents that inherent safety deficiencies have contributed to. This includes use of unnecessarily large amounts of hazardous substances and unavailability of equipment for moderation of hazardous effects. Besides, the Piper Alpha disaster is an offshore example where lack of simplification in design and procedures shows the implication of inherent safety (Paté-Cornell, 1993).
There are several contributions on the philosophy of inherent safety, including its principles and application to different aspects of high-risk technologies. This includes process concept evaluation (Rahman et al., 2005), process route planning (Palaniappan et al., 2004), plant layout design (Tugnoli et al., 2008), process safety management (Amyotte et al., 2007), process life cycle (Hurme and Rahman, 2005) and so on. Implementing inherent safety in relation to maintenance has been mentioned by Hurme and Rahman

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(2005), and this revolves around maintaining the inherently safer features (e.g. human machine interface) built into an installation and designing systems for human-error-tolerant repair and assembly. Besides, the identified literature on offshore application focused more on the oil and gas production equipment and process design (Khan and Amyotte, 2002). However, in this paper, the main objective is to apply inherent safety to maintenance in the operational phase to prevent major accidents.

The rest of this paper will continue with an overview of the risk reduction strategies applicable offshore, potential applications of the inherent safety principles to maintenance offshore, an offshore case study and then the conclusions.

2. Overview on risk reduction strategies applicable to the offshore petroleum industry

Based on several sources, including (Bollinger et al., 1996) and (Hendershot, 2006), the risk reduction strategies applicable to the offshore petroleum industry include: (i) Inherent safety, (ii) Passive strategy, (iii) Active strategy, and (iv) Procedural strategy. These are described in the following.

2.1 Inherent safety

The word “inherent”, according to Collins English Dictionary (HarperCollins, 2003) means “existing as an inseparable part; intrinsic”. Hence, inherent safety can be seen as safety which is built into or inbuilt in a system (e.g. a process plant) as an intrinsic (i.e. not acquired from operational strategies) property of the system. Inherent safety is also known as intrinsic safety (Kletz, 1977).

In other words, inherent safety may also be seen as self-perpetuating safety. The word “self-perpetuating” according to Collins English Dictionary (HarperCollins, 2003) is defined as “(of machine, emotion, idea, etc.) continuing or prevailing without any external agency or intervention. Hence, inherent safety can be seen as safety that exists and remains (internally) in a system regardless of active safety systems (external), passive safety systems (external) and operational procedures (external).

Based on Perrow’s normal accident theory (Perrow, 1984) and as supported by Hendershot (2006), increasing the number of safety systems will increase complexity. This may be difficult to manage, leading to or escalating an accident. This contributed to the Piper Alpha disaster (Paté-Cornell, 1993). There is also the economic burden of maintaining several safety systems throughout a plant’s life cycle. Inherent safety can be seen as a means of avoiding the aforementioned problems by limiting concern for equipment and human unreliability, without compromising safety and economy (Hendershot, 2006). However, there exists a warning for the inherent safety engineer, according to Hendershot (2006), which is to watch out for “dubious” options related to the principles which may eliminate or reduce one hazard but lead to the creation or escalation of another.

According to Bollinger et al. (1996), inherent safety reduces risk through the application of “minimize”, “substitute”, “moderate” or “simplify” principles in relation to the inherent properties of hazards or sources of hazards. “Minimize” is focused on minimizing hazardous materials and activities. “Substitute” is focused on the use of alternative materials, equipment, processes or procedures that will reduce risk. “Moderate” is focused on the reduction of the risk by modifying relevant properties of the hazards, e.g. by dilution, cooling, scrubbing, flaring, purging, pelletizing, granulating, operating at relatively safer conditions etc. “Simplify” is focused on the elimination or reduction of opportunities for hazardous errors through design for usability as well as by making systems, processes, procedures and organizations as far as reasonably practicable less complex or complicated.

Other principles that may also be considered as inherent safety principles include “Separate” and others in relation to the inherent safety design objectives specified in NORSOK Standard S-001, “Fail-safe design” and “Fault/error tolerance” (Standards Norway, 2008). “Separate” is focused on separating hazardous materials/occurrence and activities in space (and perhaps also in time). Some authors, e.g. Tanabe and Miyake (2013), have mentioned separation in space, but separation in time has not been identified in all the inherent safety literatures reviewed. “Fail-safe design” is focused on ensuring that a system's or procedure’s design prevents or mitigates hazardous consequences in the event of a system's failure, failure to perform a procedure or performing a procedure wrongly. “Fault/error tolerance” is focused on ensuring that errors are prevented and that no single failure/error leads to a serious accident.

The principles are seen as different ways to realize an inherently safer plant or operation (Etowa et al., 2002).

Several authors have defined inherent safety in different ways, however the meanings are related. Notable examples are presented as follows:

(1) Inherent safety “is a proactive approach for hazard/risk management during process plant design and operation” (Khan and Amyotte, 2002). It is an approach that “tries to avoid or eliminate hazards, or reduce their magnitude, severity or likelihood of occurrence by careful attention to the fundamental design and layout” (Khan and Amyotte, 2005).

(2) Inherent safety is a philosophy that “focuses on eliminating hazards or minimizing them significantly, to reduce the potential consequences to people, the environment, property, and business” (Hendershot, 2006).
(3) Inherent safety “is a philosophy which focuses on elimination of hazards or reduction of the magnitude of hazards rather than the control of hazards” (Mannan, 2012).
(4) An inherently safer process “avoids or reduces hazards instead of controlling them, (relying) on naturally occurring phenomena and robust design” (Palaniappan et al., 2004).
(5) Inherent safety is “a primary prevention method (that) aims to use safer chemicals and operations to remove the possibility (not probability as associated with added protective measures - secondary prevention method) of accidents or minimize or reduce their consequences” (Edwards, 2005).
(6) Inherently safer designs “employ a variety of techniques (hazard elimination, consequence reduction and likelihood reduction) to achieve classical risk reduction through design” (Moore, 1999).
(7) An inherently safe installation “relies on the reduction or elimination of hazardous materials or processes through changes in the chemistry, physics and physical design of a process rather than relying entirely on layers of add-on protection” (Moore, 2013).
To summarize the above, we can conclude that inherent safety is a philosophy that aims to reduce the frequency and potential consequences of accidents in a sustainable way by applying some basic principles related to green chemistry and engineering to eliminate or reduce hazards.

2.2 The passive strategy

This reduces risk through systems that can reduce the probability or consequence of hazardous events without the activation of any device (Hendershot, 2006). Examples of passive safety systems/barriers are vessel walls, fire walls, blast walls, bunkers, flame arrestors, detonation arrestors, open vents, dikes, underground drainage systems etc. A passive safety barrier, as defined by Rausand (2011), is “a barrier that is integrated into the design of the workplace and does not require any human actions, energy sources, or information sources to perform its function.”

2.3 The active strategy

This reduces risk by the help of systems that can reduce the probability or consequence of hazardous events by being activated (Hendershot, 2006). Examples of active safety systems/barriers are deluge systems, safety instrumented systems, interlock systems, emergency shutdown systems, relief valves, etc. An active barrier, as defined by Rausand (2011), is “a barrier that is dependent on the actions of an operator, a control system, and/or some energy sources to perform its function.”

2.4 The procedural strategy

This reduces risk through the application of procedures in safety management. Examples of procedural safety systems are work permit, training, standard operating procedure, safety regulations, emergency response procedure (Hendershot, 2006), risk based maintenance management etc.

3. Application of inherent safety principles to maintenance in the offshore industry

In this section, examples of how the principles of inherent safety could be applied to maintenance work offshore are presented.

3.1 Minimize

General maintenance-related examples include:
(1) Eliminating/Isolating as much hazards as possible before maintenance work.
Situations where this is demonstrable include: Providing temporary containment for leakage from a pipeline to be repaired and disconnecting a leaking pipeline from the flow system before repair.
(2) Reducing the amount of hazard before/during a maintenance activity.
Situations where this is applicable include: (i) The reduction of a pipeline operating pressure below the normal value during pigging and (ii) flushing a pipeline with water in order to remove hazardous materials before hot repair work.
(3) Reducing the frequency of hazardous maintenance tasks as far as reasonably practicable when they are unavoidable.
One way in which this can be practiced in optimizing the pipeline pigging cycle/frequency.

3.2 Substitute

Maintenance-related examples include:
(1) Replace hazardous maintenance equipment with less hazardous ones.
One way of realising this is through the selection of suitable maintenance equipment in relation to the classification of hazardous areas (zoning), e.g. using only intrinsically safe gadgets and instruments near

wellhead during maintenance, using only maintenance equipment with a certified category number (e.g. category 1 marked equipment) in the corresponding hazardous zone (e.g. zone 0 or 20). Other areas of application include: (i) substituting a coarser abrasive media for a less coarse one prior to abrasive blasting in order to reduce the amount of energy being given off as sparks or light on impact, (ii) using a compressor that provides the minimum capacity required for abrasive blasting job, thus operating with minimal amount of pressure, flying objects, sparks or static electricity, (iii) substituting sling wire for sling belt in the handling of bare pipe in a flammable zone, (iv) using a cold cutter in place of oxyacetylene torch for cutting through a piping dead-leg and (v) replacement of defective pipe fittings and valves with ones that have appropriate ratings.

(2) Replace a hazardous maintenance procedure/technique with a less hazardous one.

One way of achieving this is by substituting diving with the use of remotely operated vehicles (ROVs) and autonomous underwater vehicles (UAV) to reduce or eliminate the need to expose maintenance workers to certain hazardous tasks offshore (Khan and Amyotte, 2002). Another situation where this principle can be applied is during pressure testing of containment systems after repair by welding or the like. Between hydrostatic test and pneumatic test, the former is preferable for investigating the integrity of vessels. Pneumatic test uses compressed gas or air to check for leaks, usually with some kind of fluid such as soapy water on the joints (if it bubbles then there’s a leak). Hydrostatic test uses water pressurized in the system (if there’s leakage then water will be released from the leak source). Hydrostatic test is safer and preferable between the two options. The consequences of a fracture in a pneumatic test can be much more severe than in a hydrostatic test, since the stored energy of compressed gas is so much higher. However, for critical systems offshore, helium gas test is the most preferable since leaks are more easily detected by virtue of its smaller molecules in addition to being non-explosive.

3.3 Moderate

Maintenance-related examples include: (i) Inerting flammable work area with nitrogen foaming/purging prior to maintenance-related hot work (e.g. cutting, welding, hot tapping and hot-bolting) and (ii) mixing abrasive media with water during abrasive blasting in order to reduce hazardous effects from the abrasive material and the surface being worked on.

3.4 Simplify

Maintenance-related examples include:

(1) Developing maintenance plans/programs for maintainability and safety.

This is demonstrable in the following: (i) Spare parts optimization for critical equipment and (ii) Pre-installation of facilities for ensuring that during flammable fluid transfer all dispensing equipment and the tank being filled are bonded and grounded. This will eliminate the discharge of static electricity which may lead to a major fire or explosion.

(2) Eliminating error opportunities in unnecessary equipment (and perhaps also size), process, personnel and procedures.

This is demonstrable in the replacement of a long length of pipeline directly at sea starting with pipe lengths welded together on a lay barge to form the pipeline as it is laid on the sea bed rather than joining pipe lengths together on land into a continuous pipeline and then transporting it out to the site for laying on the sea bottom. This aspect of the principle is also practicable in the use of a relatively small remotely operated vehicle (ROV) with a simpler human-machine interface (HMI) around subsea risers in order to minimize the risk of collision.

(3) Avoiding complications in the organisation of maintenance.

Relevant applications include: (i) Ensuring proper and timely communication with a simple and precise permit to work (PTW) system, (ii) avoiding the use of a single permit for multiple jobs, (iii) avoiding ambiguities in procedures and (iv) ensuring that a situation that requires managing high-pressure operations in a platform network with only remote (at best) is not hindered by distributed decision-making.

3.5 Separate

Maintenance-related examples include: (i) Separating flammable fuels and hot-work activities in space by locating the fuel storage reasonable distances away from the worksites and (ii) separating hazardous activities and unexpected environmental hazards in time by suspending work to continue at a safer time.

3.6 Fail-safe design

Maintenance-related examples include:

(1) Fail-safe equipment

A potential application is such that ensures that the failure of a remotely operated vehicle (ROV) or an autonomous underwater vehicle (AUV) during a leak repair does not lead to a collision with the affected containment system to avoid a rupture.

(2) Fail-safe procedures
Potential applications include: Using a default “danger” signal as part of the operating procedure of a ROV or an AUV such that in case of a fault in the signalling system, an incapacitated operator, or the unexpected encroachment of another watercraft, the encroaching vessel will never be shown an erroneous "clear" signal. Another possible procedure-based application is the design and use of electronic permit to work (ePTW) system with step-by-step processes and fail-safe prompts and checks to ensure compliance.

3.7 Fault/error tolerance
Maintenance-related examples include: Designing maintenance procedures that will make installation error associated with use of wrong part, reversed installation, incorrect attachment, omission or incorrect connection impossible, ensuring that no single failure in a remotely operated vehicle (ROV) or an autonomous underwater vehicle (AUV) or in a maintenance procedure should lead to a serious accident.

4. Case study: Inherent safety lessons from Piper Alpha disaster (an offshore example)

4.1 Accident description
On July 6, 1988, the Piper Alpha platform experienced a series of explosions in the North Sea, resulting in gas risers ruptures, subsequently causing the structural collapse of the platform and the death of 167 people (Paté-Cornell, 1993). A condensate pump under repair and not tagged-out was mistakenly used to replace a faulty one due to a failure of the permit-to-work system (PTW) that did not guarantee effective communication between the two shifts involved (Paté-Cornell, 1993).

4.2 Discussion on related inherent safety principles
The associated inherent safety principles are presented as follows (Paté-Cornell, 1993):
(1) Maintenance-related: Multiple jobs were allowed on a single work permit and the formal work procedures were probably too complicated for the maintenance personnel that they decided to take shortcuts in order to lessen the workload. Besides, a night-shift operator could be ignorant of which permits had been closed out and which equipment had been set aside for maintenance, unless he was involved himself. “Simplification” of the procedure to eliminate the source of the hazardous action was necessary.
(2) Design-related: The design of the facility lacked the capacity to sustain high temperatures and direct heat loads for a long time. “Substitution” of the design with a more robust option was necessary.
(3) Design-related: The design philosophy created fatal failure dependencies and tight couplings. “Simplification” of the design was necessary to prevent an unwanted event from being compounded.

5. Conclusions

Although the use of inherent safety has not been as widespread as that of techniques such as HAZOP and quantitative risk assessment, it is arguably the most robust and cost-effective safety strategy (Khan and Amyotte, 2002). However, significant amount of work that has been done to show its effectiveness tended to focus more on design. There is the need to apply the principles thoroughly in other phases of a plant’s life cycle, most especially with respect to human operational activities which have contributed to several major accidents and still have the potential to contribute to more.
The intention of this paper has been to apply the principles of inherent safety to the prevention of maintenance-related major accidents on offshore installations. This is driven by the need to fill the risk reduction gap that procedural, passive and active risk reduction strategies have not been able to close over time, e.g. as evident in the discouraging number of hydrocarbon leaks on the Norwegian continental shelf which maintenance significantly influenced (Vinnem et al., 2007).
The result of this endeavour is the adaptation of the principles of inherent safety to maintenance and the presentation of some robust and cost-effective examples based on inherent safety for the prevention of maintenance-related major accidents in the offshore industry.

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