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CHEMICAL HAZARDS AND SAFETY BARRIERS A CASE STUDY OF THE NORWEGIAN OFFSHORE OIL AND GAS INDUSTRY

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ABSTRACT

During the forty-five year period of oil exploration in the North Sea, there has been a radical improvement in the prevention of chemical exposure in the working environment. In the early stages until 1980 there was a lack of knowledge regarding the risk of using chemicals and the related health effects on the workers. However, the organisational, technical and legal steps taken during the intervening years led to improvement. By using the concept of barriers together with an extended "Man-Technology-Organisation" perspective, the paper assesses the measures that have been put in place in order to protect workers against chemical hazards and the barrier functions that have proven to be effective in protecting the workforce. The study shows that an effective barrier function is developed by integrating different and interrelated MTO-elements as a continuous process, in interplay with regulatory frameworks, enforcement in the chain of operators, contractors and vendors, and the developing of scientific knowledge as well as enforcement from external stakeholders in the civil sector.

Keywords: chemical exposure, offshore industry, risk regulation, MTO and barriers

1. INTRODUCTION

Chemical hazards can be associated with the most severe industrial accidents. In the European context, the Seveso disaster in Italy (1976) led to new regulation as the Seveso Directive claiming better safety assessments and procedures for planning and implementing hazardous industrial activities. In the Bhopal disaster in India (1984) more than 3,000 people were killed after the release of highly toxic vapors at a Union Carbide pesticide factory. The accident led to a global concern about chemical hazards that prompted the establishment of new regulations and assessing institutions, such as the Chemical Safety and Hazard Investigation Board (CSB) in the United States. In Europe the REACH regulation was introduced in order to place greater responsibility on industry for managing the risks from chemicals used in production and to provide safety information about the substances for the people involved. Manufacturers and importers are required to gather information on the properties of their

chemical substances which will allow their safe handling, and to register the information in a central database run by the European Chemicals Agency (ECHA) in Helsinki.[1]

The purpose of this paper is to explore chemical hazards in the offshore industry by following the handling of chemical exposure on the Norwegian Continental Shelf (NCS). Compared to major hazards such as blow-outs with oil spills on the sea (Bravo, 1977), capsizes of platforms (Alexander Kielland, 1980), or explosions and fires (Piper Alpha, 1988), this hazardous working environment has received much less attention. The Cancer Registry of Norway has recorded that offshore workers in general have a higher risk of getting leukaemia, probably due to exposure to benzene. Therefore, in 1998 they established a cohort of 28 000 former and current offshore workers for the purpose of assessment (Bråtvedt & Moen, 2007). A summary of findings regarding skin illness concludes that some offshore working groups exposed to oil and oil products showed a higher frequency of skin illnesses (Moen, 2004; Steinsvåg, 2007). In the wake of recent publicity, additional research projects have been initiated by The National Institute of Occupational Health (STAMI), the Norwegian Oil Industry Association (OLF), and the individual companies. These studies focus on the effects of inhaling oil vapour, the use of isocyanides, exposure to nanoparticles in welding smoke, and activities coined as “hot work” (Sjonfjell., 2005).

The purpose of this paper is to explore two areas: (1) What measures have been put in place in order to protect workers against chemical hazards? and (2) What are the barrier functions that have proven to be effective in protecting the workforce?

2. THE REGULATORY CONTEXT

Two perspectives on the regulatory arena are useful as contextual framing of the study. The first one is the development of the Nordic model of occupational health and safety (Karlsen & Lindøe, 2006) and its role in developing safe and productive workplaces. The second one is the specific regulatory approach within the offshore petroleum industry. Kurt Lewin (1890-1947) identified the research methods known as “action research” (Weisbord, 1990), where the core element was to assist stakeholders in their improvements through participative and democratic methods. Lewin´s principles of solving organizational conflicts were developed further through socio-technical theory, combining the interaction between people (the social system) and the technical elements in organizations or institutions. The Industrial Democracy Projects conducted in Scandinavian industries throughout the 1960s applied socio-technical systems and workplace designs through large-scale experiments (Emery & Thorsrud, 1976). The results of these experiences were incorporated into the new working environment regulations for the purpose of harmonizing quality of working life for employees with productivity and management concepts. A comparative analysis of the Nordic and the European countries shows that the Nordic OHS regulations, although obviously not uniform, became genuinely different from those found elsewhere in Europe at the time (Vogel, 1998, pp. 11-32). Later on, the EU and some member countries used elements from this model in their redesigning of OHS industrial regulations (Karasek & Theorell, 1990; Rogowski & Wilthagen, 1991).

The first phase of risk regulation on the NCS began in the early 1970s, and it coincided with a new regulatory process on OHS in the UK. The initiative came through the Robens Committee that raised a debate on how to balance flexibility with prescriptive regulations and involvement of the workforce (Reason, 1997). These new trends in regulation merged with the development of the Nordic model for regulating the working environment, resulting in the new WEA (1977). From its establishment in 1972, the Norwegian Petroleum Directorate (NPD) played a leading role in the development of a new offshore safety-regulation regime (Karlsen & Lindøe, 2006). The government allocated resources for a research program called Safety at the Shelf (1978-1981) in which NPD, the industry, and research institutions developed new principles, methods, and practises (Hovden, 2002). New legal principles (enforced self-regulation and functional requirements) were introduced throughout the 1980s. The External Reference Group for Regulatory Development, based on the tripartite collaboration between authorities, employers, and unions, was established in 1985. Later renamed the Regulatory Forum, the organisation represented the interests of the Norwegian Pollution Control Authority and the health authorities (Braut & Lindøe, 2008).

The barrier concept plays an important role in Norwegian offshore safety regulations, and the concept is embedded within the guiding principles of Section 5 of the Management Regulation:[2]

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[1] http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm

2 (www.psa.no/management)

Barriers shall be established that: a) reduce the probability of failures and hazard and accident situations developing, b) limit possible harm and disadvantages.

Where more than one barrier is necessary, there shall be sufficient independence between barriers. The operator or the party responsible for operation of an offshore or onshore facility, shall stipulate the strategies and principles that form the basis for design, use and maintenance of barriers, so that the barriers' function is safeguarded throughout the offshore or onshore facility's life. Personnel shall be aware of what barriers have been established and which function they are intended to fulfil, as well as what performance requirements have been defined in respect of the technical, operational or organisational elements necessary for the individual barrier to be effective. Personnel shall be aware of which barriers are not functioning or have been impaired. The responsible party shall implement the necessary measures to remedy or compensate for missing or impaired barriers.

3. METHOLOGY

Norwegian research institutions have monitored the Norwegian oil and gas industry during the last 35 years, with a portfolio of projects related to technological change, safety management, and regulation (Olsen & Lindøe, 2009). By choosing chemical hazards as a 'case', it has been possible to select information from different data sources, with the purpose of identifying some main generic features that can provide valid knowledge about the industries' responses to the hazards over a long period (Yin, 2003). Comparable and relevant statistics of indicators are not available for the whole period. We have chosen document analyses as the main source for data collection, complemented with the testimony of key informants. By choosing among a collection of relevant written materials from various sources—observations, statements, and opinions from both employers and employees can be represented.

Stakeholders	Documents
Authorities	• White Papers to the Storting (Parliament) on offshore safety
Regulating agency	• Annual reports from 1975 to 2003 • Reports on the monitoring of safety (RNNP) • Special reports on chemicals and the work environment
Industry and unions	• Protocols of negotiations regarding working with mud • Members magazines
The public	• Articles in newspapers on "The oil mare" (2005)
Scientists	• Commissioned reports and journal articles

A main source of information has been the members' magazine from one of the two main unions. In this publication we have followed the issues of chemical hazards for a period of 22 years (1978 – 2000) by searching for articles (information, debates, reports, etc.) dealing with chemical hazard. There may be both pro and con arguments for using a members' magazine. The pro argument can be stated as follows: The magazine represents a continuous stream of information and documentation from a main stakeholders' perspective, including their perceptions and opinions on the risk and how it has been handled by the regulators and the industry. The magazine covers debates, opinions, criticism, reflections, etc. A stakeholder perspective is seen as important within the emergent concept of risk governance, and the authorities as well as the industry have accepted the unions as a competent and critical acting party regarding safety issues. The con argument involves the bias inherent in following a magazine that represents unions—in their selection of topics, use of sources, possibility of ignoring data, etc. However, an awareness of this bias, together with multiple sources of information, serves to counterbalance the disadvantage of using the source. Furthermore, additional documentation sources have been selected in order cover perspectives from authorities, industry and scientists.

The document analysis was supplemented by in-depth interviews with thirteen key informants, representing various sectors: industrial leaders (3); OHS experts (4); union leaders (1); workers from operators (2); and from contractors, entrepreneurs, and/or service industries (3). The workers represented roughnecks (drilling deck), well service, and cleaning/coating surfaces.

The issues in the interview guide were categorized according to our theoretical perspectives covering these topics: (1) the chemical environment in a long-term perspective; (2) milestones regarding establishing barriers over time and within the perspectives of individual, technological, organizational and regulatory approaches; (3) Who are the main actors or innovators? (4) the requirements, the development, and the use of personal protection equipment; (5) the use of measurement equipment; (6) the role of safety delegates; and (7) the balancing of productivity and safety. The time frame allocated for interviews was about one and a half hours; and the guide was used in a flexible way, reflecting the role, position, and competence of the informant. The interviews were tape-recorded and transcribed. Data collected from our empirical findings in the documents and from the interviews were sorted out into appropriate time periods of the four decades from the mid-1960s.

4. ANALYTICAL PERSPECTIVES

Our analytical framework is based on two complementary analytical perspectives: the concept of barriers and a socio-technical perspective called Man-Technology-Organization, frequently referred to with the acronym MTO.

Barriers

The concept of "barrier" is widely used to denote some form of obstruction towards an emerging threat or accident (Hollnagel, 2004, pp. 68-108). Reason (1997, pp. 9-12) recommends a strategy of finding active failures and latent conditions for potential accidents, and he develops the "Swiss cheese Model" as a metaphor for in-depth defense (a system of barriers). Even though there is neither a universal definition of the barrier concept nor any agreement regarding the effect of barriers, some common features can be found in the literature. Sklet (2006) specifies that it is common to distinguish between *barrier functions* and *barriers systems*. A barrier function means a function which can stop the evolution of an emergent accident so that the next step in the chain does not occur. A barrier system consists of several barrier elements of different types (technical, operational, human, software, etc.), and these elements maintain the barrier's function. Different definitions of barriers cover or include the prevention, the control, and the mitigation of an accident. Based on the synthesis of common features, Sklet (op.cit.) summarizes the following three characteristics of a safety barrier:

- *Safety barriers are physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents*
- *A barrier function is a function planned to prevent, control and mitigate undesired events or accidents*
- *A barrier system is a system that has been designed and implemented to perform one or more barrier functions.*

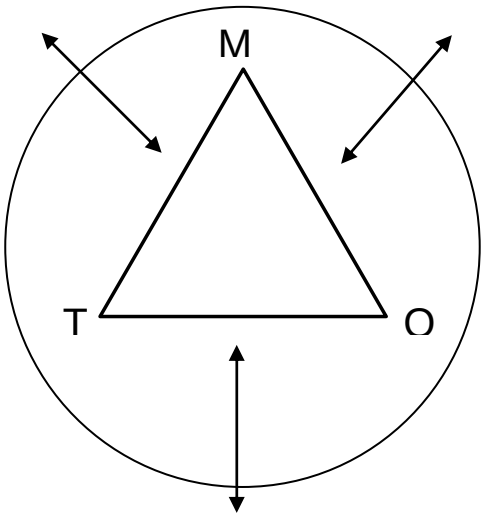
In the effort to prevent hazards leading to major accidents, such as hydrocarbon release on platforms, the understanding of the implementation and use of barriers has been an important issue (Sklet, 2005).

An extended MTO perspective

The offshore petroleum sector is part of a wider global energy sector with a diversified group of stakeholders: oil and gas producers and consumers with interests in safeguarding energy resources, local municipalities looking for new industrial sites for petroleum activities, and a strong movement of environmentalists, etc. The societal response of regulation is a compensation for market failure, informing public opinion and making premises for political priorities and decisions (Baldwin & Cave, 1999). The regulators manage a three-fold process of gathering information about risk, producing norms (laws, regulations, and legal standards), and managing the enforcing of mechanisms of control and of sanctions (Hood, Rothstein, & Baldwin, 2001).

By combining the intra-organizational perspective of MTO with the framework of external factors, it is possible to establish an "Extended MTO-model" as shown in figure 1.

Extended MTO-model **External Contextual Factors**



Market Factors

- Competition
- Capacity
- Contracts

Knowledge

- Research efforts
- Expertise

Regulation

- Laws and regulations
- Principles
- Role of agencies

Civil Society

- Unions
- Public opinion/Media
- Organized interests
- Civil society

Figure 1. An extended MTO-model

The Man-Technology-Organizational model has been a popular way of presenting the complex system of social and technical entities among industrial actors and regulators (Olsen & Lindøe, 2009; Rollenhagen, 1997). The MTO-model has a forerunner in the development of socio-technical theory in the 1960s leading to the Working Environment Act in 1977.

5. FINDINGS

The presentation of our findings is grouped under four main categories: (1) assessment of the chemical working environment, (2) communication on risk issues, (3) personal protective equipment, and (4) technological changes. The company's assessment of their (chemical) working environment and the communication on hazardous issues is seen as an organizational factor, while technological change includes improvements in design and equipment. Personal protective equipment can be related to the individual worker and his mindset, the accurate interpretation of information, and expertise in using the equipment. However, it may also be seen as part of the organizational effort and technological improvement.

Assessment of hazards

In the first phase of exploration from 1966 up to the 1980s, knowledge about risk and harmful effects on workers' health from chemical exposure was limited, and competence among the regulators, as well as throughout the industry, was very weak. Neither the occupational safety and health organizations nor the unions were focused on chemical hazards. When the drilling operation began in 1971, both the technology and the management culture were dominated by US companies and an authoritarian management style. In these operations personnel in well-service and maintenance came into direct contact with hazardous chemicals. However, criticism and unwanted questioning were met with ignorance from the companies, and workers were afraid of losing their jobs (Ryggvik & Smith-Solbakken, 1997). The scarcity of a knowledge base limited the industry and the regulators in establishing scientific-based criteria for exposure, and industrial standards for

defining safety limits had not yet been developed. Although superior claims on risk regulations were in place, the industry did not follow up. With a background in maritime regulation using technical assessment, the NPD was from the beginning technically-oriented regarding safety and had less focus on the working environment. The interest and attention in personnel protective equipment was low among companies as well as among workers.

In the 1980s both the regulators and onshore industry put mercury and asbestos high on their agenda, and assessment and communication on these issues also influenced offshore activities. Otherwise, awareness of chemical hazards and systematic measuring of exposure was very limited. From time to time safety deputies and union representatives complained about job-related occurrence of illness, and that resulted in increasing attention from unions regarding hazardous chemicals. However, the requirements in WEA and other regulation regarding chemicals came into force, and as a result NPD began filing monthly reports on caretaking by companies of the working environment.

During the 1990s there were still few measurements of chemical exposure, and little attention was given by the unions. Inspections from NPD revealed poor risk management of chemicals, and they initiated a process of risk analysis. The understanding of how chemicals affected the workers was limited. In the same period NPD establish a database for work- related disease and the industry initiated research projects directed at finding substitutes for carcinogenic paints. In addition, the industry developed their ChemiRisk-project (www.ohs.no/ChemiRisk). A series of articles was presented in a major newspaper over a long period and coined the “Oil Nightmare” crisis that directed a massive focus on the hazards and illnesses following chemical exposure. These stories boosted the effort made by authorities and the industry toward better management of chemical hazards.

The unions and NPD followed up by requiring more information and informative datasheets from the industry, and chemicals became an issue at safety meetings. In the 1990s NPD enforced their directives through datasheets and with the use of sufficient and correct personal protection equipment (PPE). Companies began to establish task forces and chemical committees that worked to develop substitutes for hazardous chemicals, and OLF established an acceptance procedure of qualifying datasheets. Later on the industry took coordinated initiative on research projects and became an active user of ChemiRisk. New regulations on chemicals came into force with the REACH regulation. Finally the offshore database for chemicals was completed, and workers expressed their appreciation of information on hazardous chemicals.

For some years the unions have challenged the industry and the regulators on the obvious problems of chemical risk, the industry’s lack of systematic risk assessment, and the management of offshore chemical hazards. During the years 2005 – 2006 the newspaper *Dagbladet* published a series of articles under the heading “The Oil Nightmare” which included aggregated cases and personal stories from offshore workers with cases of cancer, poison injuries, and even death. The public attention that ensued, together with the influence of the unions, resulted in an initiative from the Ministry. A group comprised of the stakeholders prepared a report (Sjonfell, 2005) and presented the documentation and findings to the Storting in a White Paper on health, environment, and safety (St. meld. 7, 2001-2002). The Petroleum Safety Authority (PSA) followed up by making chemical exposure a focus area in the “Risk Level Project” (Vinnem, 2010).

Personal protection equipment

The new WEA from 1977 claimed participation from the workers in improving the working environment and preventing harm, implying there was active use of PPE. However, the industry as well as NPD documented very limited use of PPE among workers during the 1980s. There could be a number of reasons for this: lack of knowledge, ignorance regarding the use of PPEs, and PPEs not suited for their purpose or not ergonomically well-designed. Improvement of PPE was undertaken on an industrial level, and institutional means came into force as specification for CE-signing and certification procedures and the control regime became stronger. Within some areas prescriptions became more detailed, with rules for using protective glasses and extra protection suits on the piping deck. Mutual interests and better cooperation between operators and entrepreneurs created a better framework for such improvements. By the end of this period, workers stated that access to PPE as well as training and equipment was used satisfactory, and protective masks were proved to be effective when used correctly.

Technological changes

At the beginning of the offshore period a combination of open access to chemicals and mud and manual labor implied a high degree of exposure for the workers. However, the socio-technical perspective embedded in WEA claimed that workers should be protected by the design of technical equipment. In the 1980s NPD recognized the problems resulting from the limitations of the design concept, ordering closure for the systems

returning mud and citing the need for improved ventilation. However, instruments for measuring the chemical exposure were unsuitable and ineffective, and that hampered effective means of improvement.

In 1995 the new regulations bluntly clarified that workers must be separated from direct contact with pipes and equipment containing chemicals. The gradual closing of manual mud handling and increased automation became major improvements. The supply industry and entrepreneurs pushed for improvement in technology and innovative solutions, and some of the hazardous paints were prohibited. During the last decade most chemicals became encapsulated and better and easier measurement equipment have become available. The industry seems to have accepted their responsibility for technological improvement.

6. ANALYSIS AND DISCUSSION

Table 1. *Milestones of Reduction of Chemical Hazards over Three Decades*

Issues	1978 – 1989	1990 – 1999	2000 – 2009
Assessing chemical hazards	-Mercury and asbestos arrive on the agenda of concerns. -Measuring of exposure, but little of it is systematic. -WEA is established, and sets requirements regarding chemicals. -Unions focus on hazardous chemicals. - Safety deputies and union representatives complain about job-related illnesses. - NPD begins to file monthly reports about how companies take care of the work environment.	- Still little measurement of exposure occurring. -NPD claims risk analysis, but there is limited understanding of chemicals by the companies. -NPD establishes a database for work-related diseases. -Little attention by unions. -Research projects on carcinogenic paints are done. - Inspections from NPD reveal poor risk management of chemicals. -The companies respond and make improvements.	-The RNNP project starts, with the purpose of monitoring all important safety indicators. - The industry develops the ChemiRisk-project. -A critical media focus by newspapers draws attention to the "Oil Nightmare."
Risk communication	WEA files chemical datasheets. Unions require more information, and NPD calls for informative datasheets. Chemicals become an issue at safety meetings. Some companies create detailed procedures that are not followed.	NPD cites datasheets and points out insufficient PPE as a consequence. Companies establish task forces, and chemical committees seek chemical substitutes. OLF establishes safety procedures with datasheets.	Industry takes coordinated initiatives through research projects. Active uses of ChemiRisk. Chemical regulations in force. Database for chemicals is completed. REACH is implemented. Workers are satisfied about helpful information on hazardous chemicals.
Us of personal protection equipment	WEA rules that workers must use PPE, and actively contributes to preventing harm. Companies and NPD documents low use of PPE, and some PPEs are not suited for the purpose.	Claims of CE-signing. OLF initiates certification of PPE. Stronger regimens and more control occur.	Claims for usefulness of protective glasses. Introduction of "chemical suit" on piping decks. Cooperation between operators and entrepreneurs. Workers see access, training and use of PPE as satisfactory.

Techno-logical changes	-Regulations follow WEA claim that workers must be protected by the design of technical equipment. -The combination of open systems and manual works implies a high degree of exposure. -NPD orders the closing of returned mud systems and orders improved ventilation. -NPD says the problems are a result of concept and design. -Measuring instrumentation is unsuitable. A research project causes better technology and automation.	-The SAM-regulation (1995) is a milestone. -Gradual closing of mud-handling and mixing equipment. -Increased automation. -The supply industry pushes for improving new technology. -Some hazardous paints are banned. -New technology makes health improvements. -Regulatory rules separate workers from direct contact with pipes and equipment.	- Most chemicals become encapsulated for use. - There is still exposure with some equipment, but new technology is being developed. - Better and easier measurement equipment. - Improvement of equipment for "surface-workers." -The industry has accepted their responsibility for technological improvement.

In Table 1 we have summarized the process of installing improvements during the last three decades by following the four categories from the presentation of the findings.

By using an extended MTO-perspective as a prism for assessment, we may separate and identify some of the external factors that have influenced the development of the barriers—including market factors, available knowledge from the scientific community, the regulatory framework, and opinions or reactions raised in the civil sector (Renn, 2008).

Market factors

The risk from chemical hazards is a good example of why authorities use regulation as a compensating mechanism and apply necessary interventions when the market mechanisms fail or lack incentives for improvement (Baldwin & Cave, 1999). However, when risk regulations were established in the 1980s with the adoption of specific regulations for chemicals and the development of industrial standards for assessment and risk management, contractual mechanisms came into force. For the suppliers, contractors, and vendors, documentation on the safe operation of processing chemicals became a necessity for being shortlisted as tenders. As a consequence, the supply industry pushed for the improvement of personal protective equipment, the training of vulnerable and exposed personnel, and the use of "best practices."

Scientific knowledge

Lack of knowledge regarding hazardous chemicals and the amount of exposure on the workers during the initial decades is striking. Mercury and asbestos were in use in the early offshore stage, and norms were developed onshore for these agents. The exposure to chemicals mixed in mud, oil or by-products in the drilling and extracting process involved multiple problems. *Firstly*, for many chemicals used in the offshore environment, knowledge of potential risk was either limited or nonexistent. Even if the chemical properties were known from laboratory experiments or onshore industrial use, their features might change in the maritime environment and when other agents were added. Therefore, critical acceptance values were not known. *Secondly*, in the early stage the instruments needed for measuring exposure were not yet technologically well-developed. In some cases, the instruments used onshore were not suitable offshore. In other cases, the instruments became a fixed measuring point at the workplace and were not adjusted for measuring personal exposure at the actual work site. *Thirdly*, the numbers of industrial hygienists, as well as their competence regarding chemical hazards, was low from the beginning. These factors, taken together, restricted the possibility of developing effective barriers at the individual and organizational levels. This lack of knowledge influenced the unions in their actions. During the initial period they were vacillating between a proactive role as an agent of change for improvement and a more passive role.

Regulation

The situation underlines the important role of a proactive risk-regulation regime (Hood, et al., 2001), including laws and legal standards (Braut & Lindøe, 2010). A new Working Environment Law (1977) laid the foundation for a tripartite system for the industry, the regulators, and the workforce (represented by unions), where continuous improvement of both production and the working environment was a basic goal (Karlsen &

Lindøe, 2006). The WEA ruled for requirements on the use of chemicals, and the principles of internal control required the industry to document safe operations.

The regulations specified that the industry must choose solutions and barriers having the greatest risk-reducing effect, based on an individual as well as an overall evaluation and stated that collective protective measures shall be preferred over protective measures aimed at individuals. As a consequence of these principles laid down in the regulations, NPD required the industry to focus on design issues and technical barriers. The outcome of this ruling was new technical designs for processing equipment, such as encapsulating chemicals and proper ventilation, and replacing manual labor with the automation of processes. That appeared to be the most efficient means of reducing exposure, and resulted in more effective follow-up and maintenance procedures from the industry.

External public actors

The image of hazards and risks in offshore operation has been associated with major accidents, such as the Bravo blow-out, the capture of Alexander Kielland, the explosion and burning down of Piper Alpha, and major oil emissions to the sea. Unfortunately, the hazardous working environment exposure of individuals or groups of offshore workers seldom reaches the media headlines. Therefore it may be an exception to the status quo when the exposure of offshore workers to chemical hazards becomes a public issue. However, after three decades of dangerous chemical exposure it was a series of articles on "The Oil Nightmare" in a leading newspaper that attracted public and political attention. Personal stories of workers with cancer, toxic injuries, and a high death toll alarmed the minister in charge who initiated a report that became a White Paper to the parliament (Sjonfell 2005). The initiative strengthened the regulators in their demands to the industry, as well as enhanced the industry's cooperation in monitoring effects through the "Risk Trend Project."

7. CONLUSION

Two major conclusions may be drawn from the study. One conclusion is related to the dynamics of barrier functions within the complex field of hazardous chemicals, and the other conclusion concerns the usefulness of an extended MTO-model in assessing barriers and developing a robust barrier system.

The *Step-Change model* introduced in the UK describes three chronological stages of improving safety: Firstly concentrating on engineering and technical improvements, secondly by introducing organizational improvements as safety management systems, and thirdly by using the potential for behavior modification. This model reflects the three elements in the MTO-model where technology, organization, and human behavior follow step-by-step. This program has been debated and has received opposition from unions, and its scientific basis has been contested. In his assessment of the "Step-Change model" Hopkins (2011, p. 587) asserts that: "...as soon as we ask why a certain unsafe behavior occurred, we inevitably find engineering and management factors that have contributed to the behavior….In short, we find ways of eliminating or reducing risky behavior that are not dependent on behavior modification techniques." Our study's findings confirm the critique of the contested Step-Change model and contradict the popular idea of seeing improvements of safety as successive steps from engineering and technological means, through organizational systems with the modification of workers behavior as the final step.

The MTO concept has been widely used in assessing risk and improving safety in the Norwegian offshore industry. Our assessment of the approximately forty-year process of reducing chemical hazards has demonstrated the limitations of an intra-organizational MTO - perspective. There is a need to combine the MTO elements with external factors in a combined framework. That framework includes the regulatory regime, market mechanisms involving the industrial actors, the role of scientific knowledge, and the civil society with its external stakeholders. The mechanisms proven to be effective have been better regulation, new technology, organizational means, responses and attitudes of workers and unions, as well as social amplification of chemical hazards through the media.

New regulations ruled that workers should be moved away from direct contact with pipes and equipment. Following the stricter regulations, new design concepts with increased automation resulted in gradual eliminating of manual mud-handling. The supply industry and entrepreneurs pushed for improvements in technology and developed innovative solutions by substituting less toxic paints, and by introducing personal protective equipment. This equipment has seen considerable improvement, and combined with changes in behavior it became an important physical barrier. However, the effectiveness of protective equipment depends largely on many other affective factors, and has proved to be a fragile barrier. An effective barrier function is developed by integrating different and interrelated MTO elements as a continuous process—in concert with regulatory

frameworks, enforcement in the chain of operators, contractors and vendors, and the development of scientific knowledge, as well as enforcement from external stakeholders in the civil sector.

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Acronyms

CBS	Chemical Safety and Hazard Investigation Board
ECHA	European Chemical Agency
OLF	Norwegian Oil Industry Association
MTO	Man-Technology-Organization
NCS	Norwegian Continental Shelf
NPD	Norwegian Petroleum Directorate
OHS	Occupational Health and Safety
PPE	Personal Protective Equipment
PSA	Petroleum Safety Authority
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
STAMI	National Institute of Occupational Health

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