What Difference has the Cullen Report made? Empirical Analysis of Offshore Safety Regulations in the United Kingdom's Oil and Gas Industry

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Abstract

Anecdotal evidence from the United Kingdom's offshore oil and gas industry indicates that risk-based safety regulations, introduced in the aftermath of the 1988 Piper Alpha disaster, have improved safety outcomes such as reducing fatalities and dangerous occurrences. However, the empirical dimensions of this supposed improved safety record is scanty. This paper explores the relationship between the safety regulatory regime and safety outcomes in the UK offshore oil and gas industry from 1995 to 2011 using multivariate regression analysis based on the generalized linear modelling framework. We assess the trend and impact of the regulatory changes implemented through the safety case regulations on major hazard risk indicators such as hydrocarbon releases controlling for technical factors such as type of offshore facility, facility location, water depth, production levels, and external factors such as oil prices, acting as a measure of the prevailing macroeconomic activity level. The results show a statistically significant industry-wide decline in hydrocarbon releases between 1995 and 2011 (average marginal effects), after controlling for location, water depth, installation type, installation age and other factors. This reflects both the commitment of operating companies and the regulator to reducing major accident hazards in line with the principles underlying the safety case regime.

Keywords: Safety economics; risk regulation; offshore safety; oil and gas; hydrocarbon releases

1 Introduction

The UKCS is a mature petroleum province with around 43 billion barrels of oil equivalent (bn boe) produced since the late 1960s. There is potential for further remaining recoverable hydrocarbon resources in the range of 11 to 21 billion barrels of oil equivalent to be produced (Wood Review, 2014). Most of the remaining median estimate of 15 billion barrels of oil equivalent reserves lies in more technical and marginally challenging areas (Kemp *et al.*, 2014). A tell-tale sign of the region's maturity remains the number of smaller field sizes being discovered and produced compared to the significant discoveries of the 1970s and 1980s. UKCS oil production peaked in 1999 at 4.5 million barrels of oil equivalent (mmboe) per day and has since been on a decline with some increase in recent years. The production decline is a result of the overall maturity of the whole province. That is declining field sizes for new discoveries and developments and deteriorating asset performance evidenced by declining production efficiency (Nakhle, 2007;

Kemp *et al.*, 2014).[1] Despite field investments reaching all-time highs, unit extraction costs have increased across the board for remaining large fields such as Buzzard and similarly for incremental ones (Kemp *et al.*, 2014). As a result, the UKCS was one of the highest cost basins in the world in 2015 (Oil and Gas UK, 2015). For example, the average unit development cost for projects was £4 per barrel of oil equivalent (boe) in 2004, whereas this rose to £13.50 per boe in 2014 (Oil and Gas UK, 2014). Since then there have been major cost reductions but the problems of maturity remain.

A key issue against the backdrop of changing prospectivity and maturity of the basin that can go a long way in defining the future of the UKCS is the safety of offshore oil and gas installations and how this can enhance maximum economic recovery. Studying offshore safety economics in the UK's upstream petroleum sector enables us to understand the challenges faced by operators and therefore, provides an opportunity to fashion appropriate regulatory responses to safeguard the future of the industry and the over 250,000 jobs it sustains (Oil and Gas UK, 2018). This paper aims to provide both a theoretical and empirical analysis that can form the basis for policymaking in the UK's upstream oil and gas industry.

Most companies evaluate safety investments just like any other type of investment to the extent that their economic profitability depends on several other critical factors including how their financial effects are measured (Talarico & Reniers, 2016). Health, Safety and Environment (HSE) investments have been shown to improve productivity and operational efficiencies of companies at the micro-level. Regarding the business case, the productivity gains from HSE investments are the benefits associated with a more efficient and improved working process that might result in lower costs, more production or less time spent by employees on a particular assignment (Targoutzidis *et al.,* 2014; Talarico & Reniers, 2016). These investments also help companies avoid future costs related to adverse events such as a potential accident or incident (Ma *et al.,* 2016).

In the offshore oil and gas industry, there is a pressing need to understand how safety management practices and regulatory provisions have enhanced outcomes for the sector regarding compliance and minimising accidents and incidents. Health, safety and environmental regulations and systems have remained an integral part of the petroleum industry over the last three decades. Recent events such as the Deepwater Horizon accident in the US Gulf coast called into question the role of these regulations in preventing incidents and accidents. Questions have been asked by stakeholders, industry experts, policymakers, and researchers concerning the safety of offshore operations (Cohen *et al.*, 2011).

Offshore oil and gas industry players in the UKCS see the post-Piper Alpha Safety Case Regulations (SCR) positively impacting the sector's approach to the management of safety and improved safety outcomes with some reduction in injuries, fatalities, dangerous occurrences and hydrocarbon releases. Industry managers support both the Safety Case Concept and the key role the regulations play in the region's overall goal-setting approach to offshore safety. Despite this, very little analytical work has been done in exploring the nexus between the SCR regime and its impact on safety outcomes in the UKCS.

The UK offshore Oil and Gas Industry had a major epiphany in 1988 when the Piper Alpha Platform exploded killing 167 out of the 229 people on board. It left in its wake a fundamental shake-up of the industry with changes in offshore health and safety management. Efforts to improve HSE performance of the UK industry continue to take place at an incremental level. However, there is the need to assess the extent to which the regulatory framework and provisions provide an adequate conduit through which high standards of health, safety and environmental

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[1] Production efficiency is defined as the ratio of the actual production to the structural maximum production potential (SMPP) of an oil and gas installation. See: http://www.devex-conference.org/perch/resources/1705-devex-wed-fleming-auditorium-alex-spring.pdf [Accessed 02 April 2020]

protection can be attained within an enterprise-wide model of risk. Arising out of the Cullen Public Inquiry were 106 recommendations, which fundamentally changed the way offshore risk was to be subsequently assessed and regulated. In 1992, the Offshore Installations (Safety Case) Regulations[2] was passed to reduce the risks from major accident hazards to the health and safety of the workforce employed on offshore installations (Miller, 1991).

Hydrocarbon releases (HCRs) constitute one of the major accident hazards in the offshore oil and gas industry and represent a potential threat or precursor to major accidents with the risk of fire and explosions if ignited, as well as major environmental damage with spills (de Almeida & Vinnem, 2020; Olsen et al., 2015; Vinnem, 2012; Vinnem et al., 2006). For example, in the Piper Alpha accident, high-pressure condensate (propane, butane and condensate) leaked through a faulty pump flange that was restarted after maintenance. This caused hydrocarbon vapour release, resulting in several explosions (Pate-Cornell, 1992; Cullen, 1990). According to the UK's Step Change in Safety[3], one of the most common installation Major Accident Hazards is an explosion or a fire caused by hydrocarbon release. At the core of the Offshore Installations (Safety Case) Regulations 1992 (and 2005), is the ALARP principle which requires safety cases to demonstrate that major accident hazards have been identified, and the risks to people are reduced to the lowest level that is reasonably practicable (Inge, 2007). It advocates a continuous reduction in risks as a function of technological changes, among others.

When it comes to safety measurement, various performance indicators are used to benchmark safety outcomes in most industries, including the offshore oil and gas industry. These assessments are usually done using qualitative and quantitative approaches. It is also based on two main types of indicators: leading indicators (proactive) and lagging (reactive) indicators (Tang et al., 2018; Kim et al., 2019; Tamin et al., 2017; Vinnem et al., 2006). Leading (proactive) indicators identify potential problems before an accident occurs; thus, they can be measured ex-ante without an incident or accident occurring. Examples of such include using human and organisational factors to measure the safety climate, safety audits and inspections (Dahl & Kongsvik, 2018; Zhou et al., 2017; O'Dea & Flin, 2001; Flin et al., 2000). On the other hand, lagging indicators actually measure accident or incident outcomes such as the number and or severity of actual accidents or incidents (Kaassis & Badri, 2018; Rozendal & Hale, 2000).

Within this paradigm, we find several of the historical safety literature, more so in the oil and gas industry, is largely qualitative and case study based, premised on the use of either leading or lagging indicators or combination of both (Sneddon et al., 2004; Mearns et al., 2003; O'Dea & Flin, 2001). However, this is changing in the past few years with more attention being paid to quantitative safety studies (Tang et al., 2017; Gao et al., 2019). This is because while case analysis can make a more adequate analysis of a particular incident, it is often context-dependent and does not allow one to draw broader inferences – that is, it fails to address the general picture. Quantitative analysis such as applying multivariate regression analysis presents a useful complement to the existing qualitative literature although it also has challenges with using proxies for qualitative input data, thus fails to grasp all effects in detail. Nevertheless, the authors chose a quantitative approach in this paper. We present not only an adequate model to address the topic at hand, but also present testable hypotheses to empirically ascertain the efficacy of offshore safety regulations.

The principal aim of this paper is to investigate the transmission effects of the post-Piper Alpha regulatory policies in contributing to the enhanced safety levels in the oil and gas industry. An econometric model of offshore safety using hydrocarbon releases is developed to attain this objective. This allows us to ascertain the impact of the post-Piper Alpha offshore safety regime

[2] An amendment to the regulations was made in 2005 and 2015. See: http://www.legislation.gov.uk/uksi/2005/3117/contents/made

[3] See http://www.oilandgasuk.co.uk/downloadabledocs/1175/a10.%20Chris%20Hamlet,%20ADIL.pdf

regulations on hydrocarbon release incidence linked to a population of the number of the installations present in the UKCS. This is done using HCRs as an outcome measure to understand the linkage between Major Accident Hazards and Safety-Critical Elements.

The rest of the paper is structured as follows: Section 2 reviews the literature on offshore safety with an emphasis on the UKCS. We also frame our research questions and underlying hypothesis here. In Section 3, we present our underlying empirical framework and model specifications followed by some descriptive analysis of the hydrocarbon release data. The results of the various econometric model specifications are analysed in Section 4, and the conclusions and policy implications are discussed in Section 5.

2 Literature Review

2.1 Regulation of Offshore Safety in the UKCS

In addressing the issue of whether the Safety Case regime changes have improved overall offshore safety levels using reference outcomes such as accident rates or trends in major accident hazards, we need to know the specific role offshore safety regulations played in the UKCS in the pre and post-Piper Alpha period. With offshore safety becoming a major prominent issue in the aftermath of the disaster and in the light of recent accidents such as the Elgin-Franklin gas leak in the UKCS and the Deepwater Horizon oil rig in the US Gulf coast in 2010, public policy considerations have focussed on the extent to which the industry together with the regulator works collaboratively to ensure a safe operating environment for all offshore personnel.

Regulatory Regime before the Piper Alpha Accident

The regulatory focus in the UK's offshore oil and gas industry before the Piper Alpha accident was based on a set of prescriptive based rules. These rules were not only complex regarding reporting structures, but also had minimal risk weightings (Miller, 1991). From the 1960s to the 1970s, the management of the safety and welfare of people was controlled by a plethora of prescriptive rules and regulations based on industry standards, knowledge and experience (Inge, 2007; Miller, 1991; Paterson, 2000). These prescriptive regulations were based on Model Licence clauses created on the back of an outdated onshore regulatory regime for the exploration and production of oil and gas from the 1930s (Paterson, 2011).

In 1965, Britain's first offshore drilling rig, the Sea Gem collapsed, killing thirteen workers. The disaster highlighted the United Kingdom's lack of experience and ill-preparedness in dealing with offshore safety-related matters. This is because no substantive legal provisions or detailed regulatory oversight was present at the time (Kemp, 2011). In 1971, the Mineral Workings (Offshore Installations) Act 1971, the principal statute dealing specifically with health and safety on offshore installations was passed. The law mandated and placed duties on the concession owner (operator or duty holder of a facility) and installation owner to appoint an offshore installation manager (OIM). The OIM had general responsibility for safety, health and welfare on the installation as well as to maintain order and discipline on the rig (Miller, 1991). The Secretary of State as well was empowered to appoint offshore inspectors with policing powers and privileges to monitor and conduct compliance checks. This minimalist prescriptive approach to health and safety was highlighted in the work of the Robens Committee (1970-1972). The recommendations of the Robens Committee culminated in the setup of The Health and Safety Executive, a new regulatory body (Simpson, 1973). This prescriptive, detailed secondary legislation remained in place until the enactment of the Health and Safety at Work (HSW) Act 1974.The (enactment of the) Health and Safety at Work (HSW) Act 1974 became the central legislation for health and safety, covering occupational health and safety in the UK.

Following the blow-out on the Ekofisk Bravo platform in 1977 on the Norwegian Continental Shelf, the UK government set up the Burgoyne Committee to, among others, assess risk regulatory regime and the effectiveness of the Department of Energy's regulations on safety (Paterson, 2007; Miller, 1991). A key issue for the Committee centred on the jurisdictional authority for regulating and enforcing offshore safety. That is, whether under the Petroleum Engineering Division of the Department of Energy or the newly established Health and Safety Executive (Lindøe et al., 2013). The Committee in its 1980 report recommended that the responsibility for regulating offshore health and safety should be conducted by a single agency, namely the Department of Energy instead of the Health and Safety Executive (Miller, 1991). So, it remained "business as usual" with a detailed prescriptive approach under the Department of Energy.

The existing prescriptive regulations encouraged a compliance mentality rather than the sort of workplace-specific assessment of risks envisaged by the 1974 Act (Miller, 1991). Oil companies had little incentive to conduct extensive workplace-specific risk assessments to show compliance with the elements of the regulatory regime. These prescriptive regulations were ill-suited to potential offshore health and safety risks. It became amply evident with the 1988 Piper Alpha disaster.

The Piper Alpha Accident and Evolving Safety Case Regime

A fundamental review of industry operations saw the creation of a new basis for health and safety regulatory interventions in the sector following the events of the 1988 Piper Alpha disaster which killed 167 offshore workers. One of the principal recommendations of the subsequent 1990 Cullen Public Inquiry was the change of regulator from Department of Energy to Health and Safety Executive, and the adoption of the new goal-setting regime. The Offshore Installations (Safety Case) Regulations (1992) was passed as a direct outcome of the Cullen Inquiry, heralding a complete shift in the thinking of the industry from the previous prescriptive regime (Kemp, 2011; Miller, 1991). The adoption of the Safety Case Regime ensured that operators (duty-holders) present a "living" document that demonstrated their understanding of the risks and hazards associated with an offshore facility and the presence of adequate risk management measures to minimise or mitigate the risks.

The Safety Case (SC) is a comprehensive document that enjoins the operator to have identified risks using a systems-based approach, and continuously reduce them to as low as is reasonably practicable (ALARP). It also enjoins the operator to give full details of the arrangements for managing health and safety and controlling major accident hazards on both mobile and fixed installations. The regulations make it incumbent on the operator to update the safety case throughout the full life cycle of a facility in three-yearly resubmissions.[4] The SC enjoins operators to submit particulars of the plant and arrangements for the control of operations on a well, including those to control the pressure in a well, and to prevent the uncontrolled release of hazardous substances (including hydrocarbon releases) and to minimise the effects of damage to subsea equipment by drilling equipment.[5] With the introduction of the SC, the primary responsibility for the continuous reductions in major accident risks shifted from regulators to the operating companies (US Chemical Safety and Hazard Investigation Board, 2015).

According to Khorsandi (2010), three principal adequacy criteria are used to assess the safety case, namely: (1) management systems to ensure compliance with statutory health and safety requirements; (2) arrangements for auditing and reporting; and (3) major hazards identification, risk assessment, and control. Demonstrating control of major hazards is a pre-condition for an offshore facility to operate in the UKCS. It can thus be expected *ceteris paribus,* that over time the uptake of technology through the adoption of best practice standards by the operating companies which is an essential component of the SC regime would lead to lower incidents or reduce the risk of a hydrocarbon release occurring. The Safety Case gives confidence to both the

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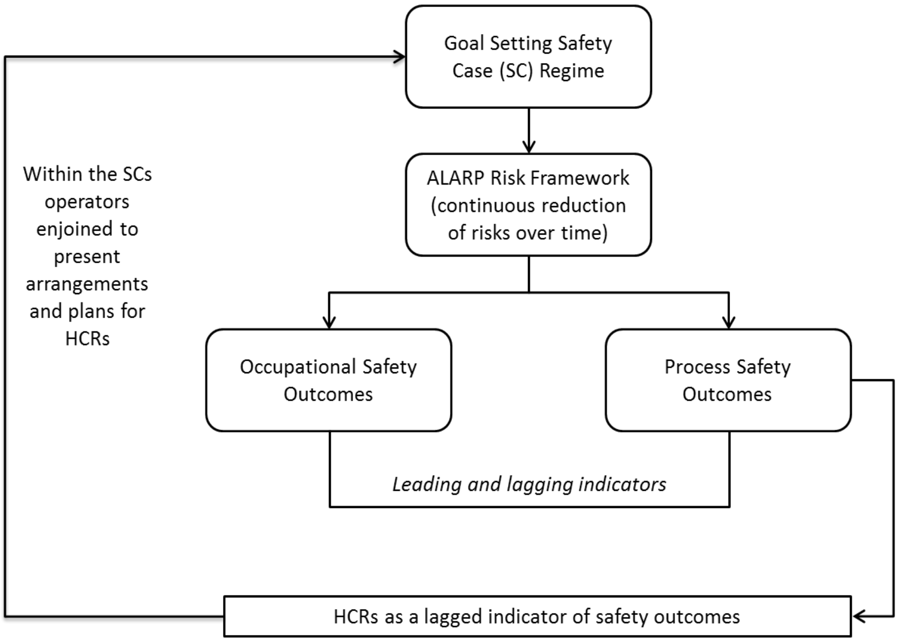
[4] This requirement has been relaxed in subsequent amendments to the regulations
[5] Schedule 2, Safety Case Regulations

duty holder and the regulator that the duty holder has the ability and means to control major accident risks effectively by providing an extra level of regulatory control on top of existing regulations (Health and Safety Executive, 2006).

The question that arises from the above then is: if the post-Piper Alpha Safety Case regime buttressed by the range of ancillary regulations are working to the extent that the operators have incorporated the continuous reduction of risks in line with the ALARP principle; then, using a lagged major hazard risk indicator of process safety outcome such as hydrocarbon releases, one would expect to observe an evidential reduction in HCRs over time (Figure 1). This would reflect the continuous efforts to the reduction of risk in line with technological advancements and increased regulatory oversight.

Figure 1 Interaction of the Safety Case Regime



Source: Author's depiction

2.2 Determinants of Offshore Safety

Several factors contribute to the prevalence of the safety climate in offshore working environments such as those prevalent in the UKCS. Following Moses and Savage (1990) and Rose (1990), we characterise the resultant offshore safety output level S_o by the following equation:

$$S_o = f(I, E, M, C) \qquad [2.1]$$

where I *= Operator's safety investments which include the costs for provisions such as maintenance, company procedures, training and experience of the workforce, installation type, age*

E *= Economic operating conditions. For example, the existence of insurance markets and premiums, oil and gas prices, society's Willingness to Pay (WTP) for safety*

M *= Regulatory surveillance mechanisms and protocols, including safety standards, inspection routines, penalties, major accident hazards controls, etc.*

C *= Operating climate such as the nature of a well or reservoir, type of production technologies and overall exposure (number of installations or production facilities present).*

Our broad categorisation of offshore safety performance leads to three sets of determining factors. Firstly, the safety investments made by the operating companies which are under their direct control and influence on an offshore installation such as the quality of the workforce, the skill base they possess, maintenance procedures, and installation equipment quality and age. It is the efficiency of an operator's safety investments and operating conditions that determine the underlying risk distribution, which in turn drives the accident or incident probabilities (Song and Mu, 2013). For example, the use of new production systems with embedded hazard control technologies in complex reservoirs such as High Pressure/High Temperature (HPHT) fields backed up by frequently scheduled maintenance activities may reduce accident probabilities caused by equipment failure. It has also been shown that extensive safety training, as well as the use of more experienced personnel, reduces error frequencies attributable to human factors. However, at some point these additional investments do suffer diminishing marginal returns (Flinn *et al.*, 1998, 2000; Cox and Flin, 1998).

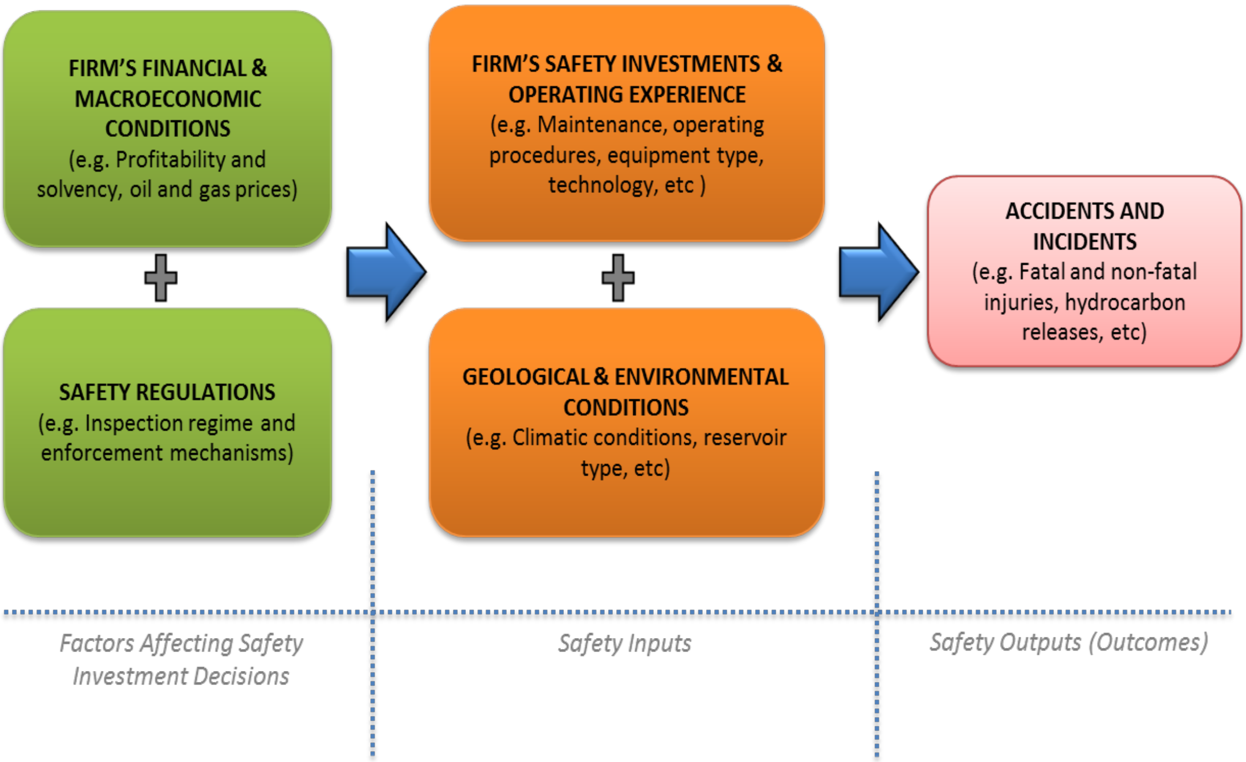
The second factor is the operating conditions. These are usually outside the control of the operator of offshore installation and include weather or climatic conditions, the features of the facility or complexity of the geological characteristics of the well being drilled, or the production facility — all of these increase the safety risks and exposure levels. For example, HPHT[6] wells have complex reservoir characteristics which can affect the safety level regarding the infrastructure needed to be put in place to produce from it safely. The probability of an incident or accident occurring is determined by the risk distribution that arises out of the interaction of these two factors, and from which the operator generates the safety outputs (Rose, 1990).

The third factor indirectly affects offshore safety performance through the effect on the operator's safety investment decisions via the safety production function. These include stringency of the HSE safety regulations and protocols and the macroeconomic environment variables such as oil and gas prices, which affect how portfolio allocation of capital and operational expenditures are carried out. For example, in a low oil price regime, firms operating in the industry usually undertake several cost-cutting initiatives to maintain profitability. Safety-critical investments are sometimes affected by these actions.

Tombs and Whyte (1998) and Kemp (2011) argue that the aftermath of the 1985-86 oil price crash, which saw the average per barrel price for OPEC crude oil drop from $23 in December 1985 to $10 in July 1986, led to the UK oil and gas industry responding competitively and collectively through the Cost Reduction Initiative for the New Era (CRINE) initiative. The initiative had an objective of achieving a reduction in capital costs by the magnitude of 30% or more (e.g. 5%-10% in fabrication costs) and also a decrease in operating expenditures. Hence, operator spending on installation investments in response to macroeconomic factors such as oil prices can affect safety levels and thus contribute to the probability of an incident occurring. The interaction of these factors is shown in Figure 2.

[6] HPHT developments are defined as developments of reservoirs with a pressure exceeding 69 MPa (10,000 psi) and a temperature above 150°C (300°F) (HSE, 2005). See: http://www.hse.gov.uk/research/rrpdf/rr409.pdf

Figure 2 Offshore Safety Performance Model



Adapted from Moses and Savage (1990) and Rose (1990)

Hypothesis Framing

With the determinants of offshore safety as our anchor framework, we formulate some testable hypotheses that allow us to ascertain the efficacy of the offshore safety regulations empirically. Our central thesis is that offshore safety performance is a function of the effect on operator's safety investment decisions through the safety production function.

The following are the other hypothesised relationships which form the basis of our study:

i. H1: HCRs are not uniformly distributed and do not occur with equal frequency across different installation descriptives such as age, location and type of structure.

ii. H2: Seasonal effects contribute to the distribution of HCRs in the UKCS under the current safety regime. That is, hydrocarbon releases do not occur uniformly over the year.

iii. H3: Age distribution effects contribute to HCR incidents in the UKCS. The probability of HCR occurrence is likely to increase as assets age and technical degradation beings to occur, all things being equal.

iv. H4: Post-CRINE era installations fabricated on cost-reduction principles have associated with them relatively more production downtimes — i.e. lower average production efficiency — and increased major accident hazards.

v. H5: Operator spending and platform investments in response to macroeconomic factors such as oil prices affect safety levels and hence contribute to the distribution of HCRs.

The literature is replete with works that examine compliance with safety climate and safety outcomes, but this is mostly concentrated on the US Gulf of Mexico. Jablonowski (2011) examined the relationship between oil spills, workplace safety and firm size using data from the US Gulf of Mexico for the period 1990-1998. The analysis supported the hypothesis that well complexity, specifically well depth and reach, increase the likelihood of HSE incidents, while other well characteristics do not. He also rejected the hypothesis that company profiles influence HSE outcomes.

Muehlenbachs *et al.* (2011 and 2013) empirically examined company-reported incidents on oil and gas production platforms in the Gulf of Mexico between 1996 and 2010. Controlling for platform characteristics such as age, they reported that incidents such as blowouts, injuries, and oil spills were positively correlated with deepwater production. Shultz (1999) found that major platform complexes in the US Gulf of Mexico were over 12 times as likely as non-major complexes to experience either an accident or a spill from 1986 to 1995. Kongsvik *et al.* (2011) observed that there were significant correlations between the number of hydrocarbon leaks on the Norwegian Continental Shelf during the 12 months before their survey and a safety climate indicator. Thus, more leaks during this period were associated with worse safety climate scores.

Vinnem and Røed (2015) examined the root causes of hydrocarbon leaks on the Norwegian continental shelf from 2008 to 2014 using the Barrier and Operational Risk Analysis (BORA) classification as applied in Norway. They found out that leaks occur most during preventive maintenance activities, which are typically carried out during night shifts. Also, they found out that 50% of the leaks are associated with wellhead area and manifolds, separation and compression systems. Additionally, they found heterogeneity between individual installations and noted that age could be a contributory factor, all things being equal.

Olsen et al. (2015) examined the drivers of safety performance on offshore platforms using organisational factors theory to investigate the relationships between work climate and hydrocarbon leaks. Their results highlighted significant associations between work climate factor — such as leadership, goals, behaviour and compliance — and hydrocarbon leaks. Likewise, Bergh et al. (2014) also examined psychosocial risk in relation to hydrocarbon leaks in a Norwegian oil and gas company from 2010 to 2011 using technical factors such as the number of leakage sources, installation age and weight as indicators. A psychosocial risk indicator was obtained from survey data. Their results indicated that the psychosocial risk indicator accounted for significant variations in hydrocarbon leaks while the technical factors and hydrocarbon leaks were only partially supported, based on correlation analysis.

3 Empirical Strategy: Modelling Safety Risks in the UKCS

3.1 Empirical Strategy: Model Specification and Estimation

Assuming each platform or offshore installation has a probability of a hydrocarbon release occurring in time t, then the expected number of reportable release incidents η_{it} for these installations for a certain production type (i.e. Fixed or Mobile) in location (Northern, Central or Southern areas of the North Sea) at a particular water depth (i.e. <100m, 100-700m, >700m) in an age category (i.e. < 5 years, 5-10 years, 10-15 years, 15-20 years and > 20years) can be characterized by the Poisson process given below.

$$P\,(Y_{it} = \eta_{it}) = {e^{-\mu_{it}}\mu^{y_{it}}}/{y_{it}!}\,, \quad y_{it} = 0{,}1 \qquad [3.1]$$

where $\eta_{it} = unit\ of\ observation$; i = indexes the count of hydrocarbon releases in a specific installation type category k (that is, Fixed, Mobile or Subsea) in a particular location f (northern, central or southern areas of the North Sea) in a particular water depth w (<100m, 100-700m, >700m) and in a specific age category (that is, < 5 years, 5-10 years, 10-15 years, 15-20 years and > 20years) and $t = \ year\ index$

$$\mu_{it} = expected\ mean\ count\ of\ HCRs\ in\ the\ unit\ of\ observation\ p$$

$$\mu_{it} = \ E(\eta_{it}|x_{it}) = Var\ (\eta_{it}|x_{it})$$

We fit regression models to the natural log of the Poisson (and Negative Binomial) expected value given by:

$$ln(\mu_{it}) = ln\, E(Y_{it}) = \beta_0 + \beta_1 x_{1t} + \cdots + \beta_p x_{pt} = \delta_{it}\, exp(X_{it}\beta) \qquad [3.2]$$

For offshore hydrocarbon releases (HCRs) we consider the Poisson rate parameter of the HCR releases per installation per year ϕ_i given by:

$$\phi_{it} = \frac{Count\ of\ events\ (HCRs)}{population\ size\ (total\ installations)} = \frac{\sum \mu_{it}}{\sum \delta_{it}} \qquad [3.3]$$

$$where\ t = year\ and\ i = observation\ unit$$

$$Y_{it} \sim Poisson\ (\mu_{it}) = Poisson\ (\phi_{it}.\delta_{it})$$

Our approach is to model the log of the HCR rates on a time trend conditioning for platform or installation-specific effects. Hence, since we are interested in the rates with regard to the release trends in the post-Piper Alpha safety regime. We fit a log-linear model to the log of our rate parameter given by:

$$ln\ (\phi_{it}) = ln\, E(Y) = ln\ \left(\frac{\mu_{it}}{\delta_{it}}\right) = \widehat{\beta_0} + \widehat{\beta_1} x_{1t} + \cdots + \widehat{\beta_p} x_{pt}$$

$$\mu_{it} = exp\ [X_{it}\beta + ln(\delta_{it})] \qquad [3.4]$$

The model is estimated by taking the log-likelihood function over the sum of all observation units across the observation years. The second-order condition which is the Hessian will remain globally concave as long as X is of full rank and $\exp(X_{it}\beta)$ does not converge to zero $\forall\, X_{it}$ (Hausman *et al.*, 1984; Greene, 2008; Cameron & Triverdi, 1998).

We model the Poisson parameter of the expected HCR count μ_{it} by taking the log of the expected counts N and offsetting for the population size or exposure $ln\ (\delta_{it})$ with the coefficient constrained to one.[7] Using the offset of the total installations per year within each unit of observation allows us to account for platforms characteristics which could vary due to the region/location as well as by age among other characteristics.[8]

More formally, because each of our yearly HCR counts does not have the same exposure regarding the number of platforms or installations located in the UKCS ($\delta_{it} \neq \delta_{jt}\ \forall\, i \neq j$), our expected count becomes proportional to our exposure parameter of the total operating installations per year such that $E(Y_{it}|X_{it}, \delta_{it}) = \mu_{it}.\delta_{it}$.

We estimate the impact of the potential determinants of hydrocarbon release incidents given the Post-Piper Alpha safety regime using the following specification:

$$ln(\eta_{it}) = \beta_0 + \beta_1 \Delta T_t + \sum_{p=1}^{n} Z_p \delta + ln(\delta_{it}) \qquad [3.5]$$

Where η_{it} the expected number of reportable HCR release incidents are categorised according to the rating classes, for example, the installation type and water depth. The vector Z_p represents the release incident characteristics. The estimations of this vector include dummies which capture the effects of the installation type $INSTYPE_k$; location of the offshore facility in the UKCS LOC_f; water depth of the installation $DEPTH_w$ and age of the installation $INSTAGE_a$.

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[7] See Cameron and Trevedi, 1998

[8] These specific effects are further tested out in the expanded models of the regressions

If the post-Piper Alpha offshore safety case regulations have had an impact on the probability of hydrocarbon incidents occurring by inducing better design measures and management of Safety Critical Elements (SCEs)[9] on offshore installations operating in the UKCS to deal with releases in line with the ALARP principle, then, after controlling for the oil and gas produced, number of installations captured by the exposure (offset), the water depth and other time-invariant fixed effect covariates, we would expect the estimated value of the time trend ΔT to be negative and statistically significant.

The expanded form of the full individual-specific effects model is given by:

$$ln(\eta_{it}) = \beta_0 \Delta T_t + \beta_1 OILPROD_{it} + \sum_{p=1}^{n} Z_p \delta + ln(\delta_{it}) + ln\,(\alpha_i) \qquad [3.6]$$

Potential variables considered in our estimation are listed below:

- Dependent Variable ($\boldsymbol{\eta_{it}}$): Count of the hydrocarbon releases standardized by exposure of platforms for the operating category.
- Time Trend ($\boldsymbol{\Delta T}$): Year-on-year trend variable to capture the effect of the impact of the Post-Piper Alpha Safety Case regime changes on safety outcomes using HCR release incidents as a proxy. We include a linear time trend in our estimation models to capture the impact of the regime change transmission effect.
- Installation Type ($\boldsymbol{INSTYPE_k}$): Dummies to test for the impact of installation type on the HCR incidence level. Our *ex-ante* expectation is that fixed installations would have more impact on HCR incidence occurrence compared to mobile or subsea installations since most of these have legacy infrastructure and were installed during the early operational years in the UKCS.
- Installation Age ($\boldsymbol{INSTAGE_a}$): Impact of the age band of the set of platforms for each category. We hypothesise that *ceteris paribus* accidents and hydrocarbon spills are more likely to occur on older platforms and installations.
- Location ($\boldsymbol{LOC_f}$): Dummies to test for the impact of location on the HCR incidence level. We have no prior postulates about the sign of this variable since platforms and, different types of installations can be found in all locations.
- Water Depth ($\boldsymbol{DEPTH_w}$): Dummies to test the impact of water depth of the installation on the HCR occurrence. An increase in the water depth of offshore installations implies an extensive use of more floating production systems as against conventional fixed structures. These floating systems have more complex controls such as turret mooring systems and riser pulling systems. Our *a priori* expectation is that the likelihood of release incidents occurring would increase with the water depth of the installation.
- Oil and Gas Produced ($\boldsymbol{OILPROD_{it}}$): Annual oil production (boe) from the installation categorised by the unit of observation. Our *ex-ante* expectation is that more oil production implies higher production activity, thus a higher likelihood of a hydrocarbon release occurring holding other variables constant. This is linked to the economic effect whereby higher oil prices induces operators to want to extract more barrels in a bid to profit from any upside advantages given the capacity constraints and short-term production limitations of the installations. We specifically introduce the oil price effect — including one and two lagged terms — into our estimation models using the mean dated Brent crude prices (real prices - 2011 money) for the respective years under consideration.

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[9] SCEs are the equipment systems which provide the basis to manage the risks associated with Major Accident Hazards (MAHs). Under the Safety Case regulations, an independent and competent scrutiny of safety-critical elements throughout the life cycle of an installation is conducted to obtain assurance that satisfactory standards will be achieved and maintained. See https://www.hse.gov.uk/pUbns/priced/l30.pdf

- Others: This includes parameters such as the frequency of maintenance activities on the platform and stringency of operator HSE policy proxied by the yearly platform investment expenditure. We expect the accidents and hydrocarbon spills to occur more frequently on less maintained platforms and installations.[10]

3.2 Data Sources and Descriptive Analysis

HCRs, as a measure of safety outcomes in the offshore working environment, reflect the probability that an offshore installation selected from the pool of available installations selected at random will be involved in a dangerous event. Data for the study comes from the Hydrocarbon Releases (HCR) System; offshore installations data from the Department of Energy and Climate Change (DECC); inventory of offshore installations from OSPAR and other data from the Common Data Access Limited (CDA) platform.

We cross-matched data from three separate databases using data from DECC, OPSAR and CDA to create a unique inventory of all structures that have ever operated in the UKCS. These databases containing offshore platform characteristics were crossmatched using unique identifiers and merged to create a panel containing all offshore production facilities (platforms and other installations) in the UKCS beginning from the year when each facility was installed through to 2011. After a platform or installation is abandoned, reused (reclassified or renamed), removed to shore or decommissioned, it drops out of the data set for the respective year when it was decommissioned. Information including water depth, location (area, block, and quadrant), production category, and installation and decommissioning years are included in the data set. Also, the data utilised in the modelling consists of only process related releases as per the classification used by the UK Health and Safety Executive. Thus, non-process HCRs such as diesel, lubrication, etc were not included in the modelling. These were filtered out.

There were 4,294 hydrocarbon release incidents in the UKCS from 1992 to 2012 with an average of 215 releases per year of which 192 were major releases; 2003 significant releases; and 2,099 minor releases (Figure 3). As Figures 3 highlights, despite major and significant releases consistently declining on a year-on-year basis, minor releases experienced more volatile swings from 1998 to 2012. HCRs from installations less than five years old rose significantly in the 1990s. For installations between 5-10 years, a similar downward trend in the reduction of the number of releases over the past twenty years can be noticed (Figure 4). Releases in the 10 to 15-year installation category have witnessed little change over the past twenty years. The most noticeable trend in the age category comes from releases from installations that are over 20 years of age. These releases have increased in number over the past twenty years, most especially from 2001 to 2005.

[10] Due to challenges with getting investments by operators in maintaining the facilities during the years under consideration, these are excluded from the data and thus a reduced form specification model was utilized.

Figure 3 UKCS hydrocarbon releases by severity

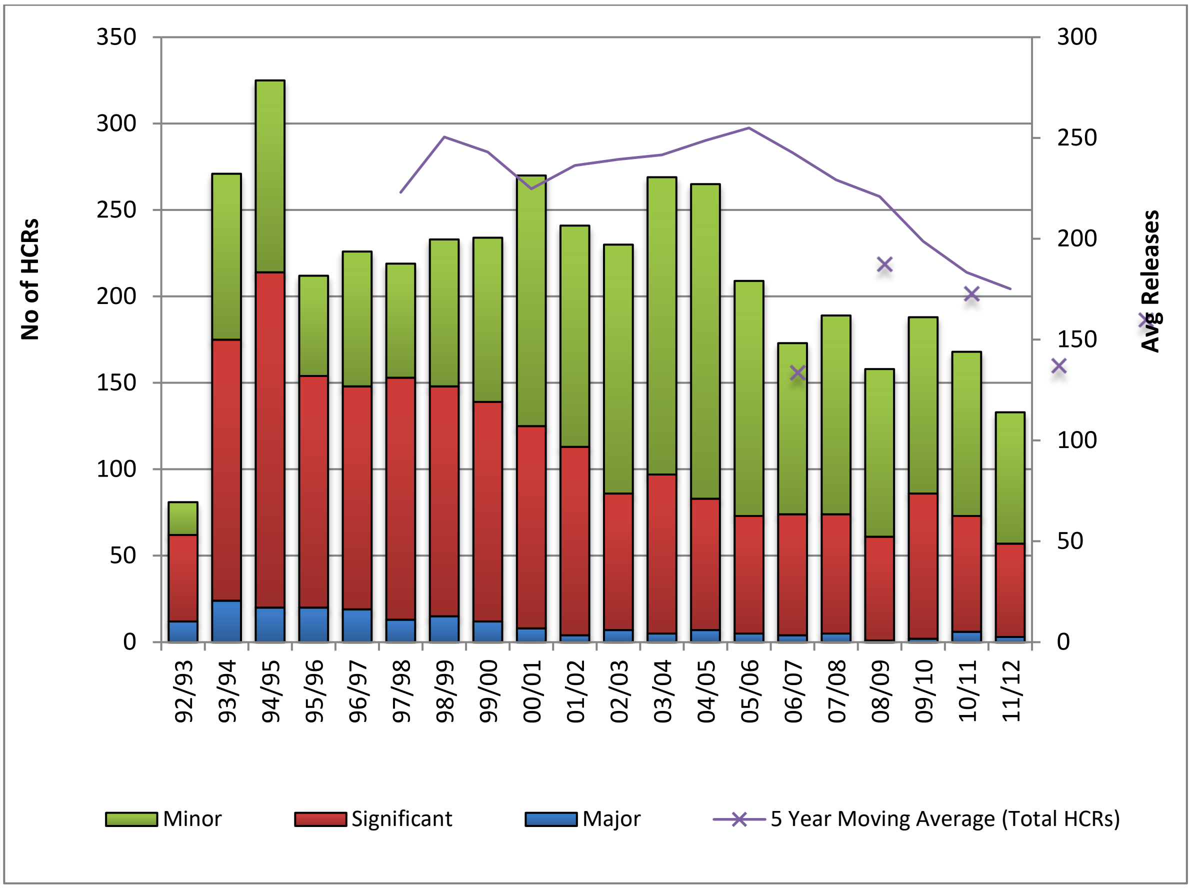
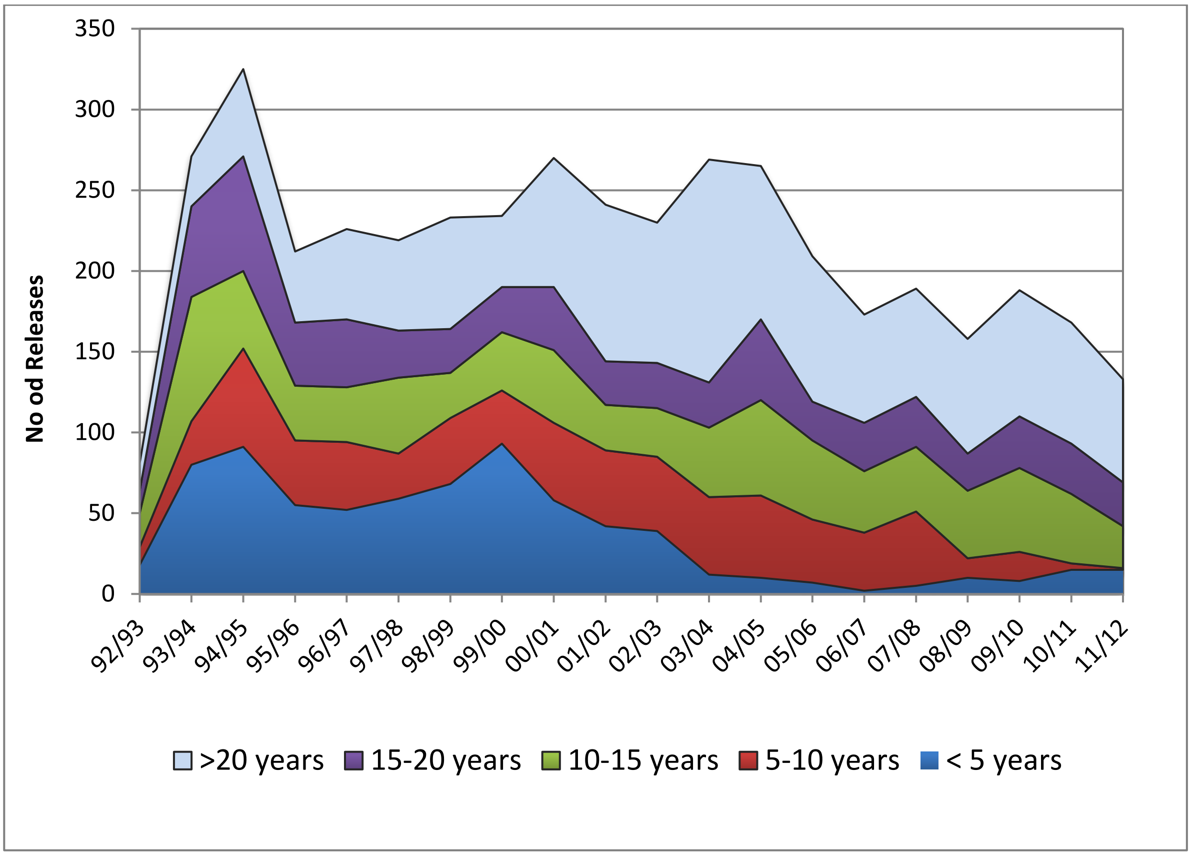


Figure 4 UKCS hydrocarbon releases by age distribution of installations



4 Results and Discussion

4.1 Poisson model with interaction terms

Table 1 below presents the parameter estimates of the Poisson model (and with interaction terms). The finding for the time trend model β_2 suggests an overall downward trend in HCR release incidents post the implementation 1992 Cullen safety case regime and subsidiary regulations in line with expectations. The time trend on the main model and all four interaction models namely location and age, age and installation type, age and water depth, and installation type and water depth was statistically significant (α=5%) downward trend in HCR release incidents post the implementation of the 1992 Cullen safety case regime and subsidiary regulations in line with expectation. There is a 3.2% overall year-on-year decrease in the number of hydrocarbon releases or a reduction in this number of 0.97 releases per installation over the 17 years from 1995 to 2011.

From Table 1, age effects estimates show that the number of hydrocarbon releases increases with the age of the installation, net of location, installation type or the water depth in which the facility is located except for those more than 20 years old. This result though not surprising, partly confirms our a priori expectation that ceteris paribus, accidents and hydrocarbon spills are more likely to occur on older platforms and installations than they would on relatively newer ones. This is because of technological factors (improved safety-critical elements and barriers) employed in the detection and control of HCRs in line with the ALARP principle of a continuous reduction in risks due to technological changes. The inclusion of the oil price parameter in the trend-oil price specification yielded statistically insignificant results.

Table 1 Incident Rate Ratios (IRR) for the Poisson Model [All HCRs]

Table 1 Incident Rate Ratios (IRR) for the Poisson Model [All HCRs]

Parameter	Time Trend Model	Time Trend and Oil Price Model	Individual Year Effects Model	Time Trend and Oil Price Model (1995-2004)	Time Trend and Oil Price Model (2005-2011)	Time Trend, Oil Price, Production Model
β_1 Intercept	0.861 (0.143)	0.858 (0.141)	0.770 (0.153)	0.770 (0172)	0.360 (0.259)	0.231 (0.209)
β_2 Time Trend	0.968* (0.007)	0.992 (0.017)	-	0.995 (0.252)	0.946 (0.034)	1.021 (0.029)
β_3 Oil Price	-	0.995 (0.003)	-	1.005 (0.100)	1.000 (0.004)	0.999 (0.04)
Installation Type:						
β_4 Mobile	1.079 (0.108)	1.079 (0.108)	1.058 (0.106)	0.935 (0.118)	1.416 (0.022)	1.078 (0.107)
Water Range:						
β_5 >100m	1.702* (0.157)	1.703* (0.156)	1.672* (0.153)	1.902* (0.216)	1.139* (0.201)	1.704* (0.156)
Location:						
β_6 Central North Sea	1.397* (0.136)	1.397* (0.133)	1.388* (0.129)	1.325* (0.148)	1.572* (0.271)	1.395* (0.133)
β_7 Southern North Sea	0.235* (0.035)	0.235* (0.034)	0.231* (0.033)	0.222* (0.039)	0.275* (0.069)	0.235* (0.344)
Age:						
β_8 5-10 years	1.147 (0.141)	1.134 (0.140)	1.368 (0.177)	0.950 (0.125)	3.020* (1.051)	1.128 (0.141)
β_9 10-15 years	1.378* (0.178)	1.385 (0.177)	1.408* (0.177)	1.226 (0.194)	3.519* (1.085)	1.391 0.176)
β_{10} 15-20 years	1.409* (0.181)	1.423 (0.180)	1.105* (0.138)	1.168 (0174)	4.258* (1.337)	1.437* (0.179)
β_{11} >20 years	1.088 (0.123)	1.084 (0.121)	1.071 (0.118)	0.882 (0.113)	3.240* (0.981)	1.082* (0.120)
Year:						
Year1996	-	-	1.018 (0.191)	-	-	-
Year1997	-	-	0.958 (0.188)	-	-	-
Year1998	-	-	0.980 (0.185)	-	-	-
Year1999	-	-	0.946 (0.190)	-	-	-
Year2000	-	-	1.080 (0.229)	-	-	-
Year2001	-	-	1.012 (0.194)	-	-	-
Year2002	-	-	0.998 (0.197)	-	-	-
Year2003	-	-	0.964 (0.232)	-	-	-
Year2004	-	-	1.032 (0.209)	-	-	-
Year2005	-	-	0.904 (0.175)	-	-	-
Year2006	-	-	0.742 (0.165)	-	-	-
Year2007	-	-	0.702 (0.162)	-	-	-
Year2008	-	-	0.578* (0.107)	-	-	-

Year2009	-	-	0.603* (0.106)	-	-	-
Year2010	-	-	0.591 (0.121)	-	-	-
Year2011	-	-	4.714* (2.563)	-	-	-
β_{12} Production	-	-	-	-	-	1.211 (0.161)
Pseudo R2	0.45	0.45	0.47	0.47	0.42	0.45
Deviance goodness-of-fit	2,018.31	2,009.39	1,904.68	1210.26	705.54	2002.32
Residual degrees of freedom	524	523	509	323	189	522
Deviance/df (Dispersion parameter)	3.85	3.84	3.74	3.62	3.73	3.84
Log Likelihood	-1678.384	-1673.923	-1621.57	-1044.52	-582.60	-1670.38
No. of observations	1,020	1,020	1,020	600	420	1,020
No. of zero-observations in the data	486	486	486	266	220	486
AIC	3376.767	3369.846	3293.14	2111.04	1187.21	3364.77

Absolute robust standard errors in brackets. *Significant at 5%

$N = 534$

IRR Estimates: The table reports IRR (incidence rate ratio) coefficients. Total number of platforms is used as the exposure term. Each coefficient is transformed into the IRR, whereby a coefficient of 1 indicates no change at all in predicted hydrocarbon releases; coefficients between 0 and 1 represent a predicted fall in releases (e.g. a coefficient of 0.88 represents a 12% decline); and coefficients greater than one represent predicted increases (e.g. a coefficient of 1.29 represents a 19% rise).

The positive sign on the installation type coefficient β_3 indicates that compared to fixed installations, mobile installations can be expected to have 7.6% more releases for each category of age band, installation, type and location. This result, though not statistically significant, deviates from our *ex-ante* expectation that fixed installations would have had a higher probability on HCR incidence occurrence compared to mobile installations. This is because most fixed installations in the UKCS have legacy infrastructure and were installed during the early operational years in the North Sea. Most mobile installations in the UKCS such as semi-submersibles and jack-up-type units used for accommodation purposes, MODUs and FPSOs have significantly newer production technologies such as logic systems that prevent or control the release of hydrocarbons.[11]

The magnitude and high statistical significance of the water range coefficient β_4 from Table shows that installations that are situated in deeper water depths (>100m) have an extra 0.53 hydrocarbon releases occurrences for each category of age band, installation type, and location. That is, installations in water depths greater than 100m have 70% $[exp\,(0.5322) = 1.703]$ more hydrocarbon releases as compared to those in water depths less than 100m in each category of location, age group, and installation type across all three models.

Similarly, for the location coefficients β_5 and β_6, the highly statistically significant coefficient of 0.3343 for the CNS indicates that installations in the Central North Sea have 0.33 more HCR releases as compared to the Northern North Sea for all age bands, installation type and water depth categories. This translates to 40% more HCRs $[exp\,(0.3343) = 1.397]$ than NNS installations with the same age bands, installation type and water depth categories. Furthermore, the statistical coefficient of -1.446 for the Southern North Sea (SNS) indicates that SNS installations have almost 1.45 times fewer HCRs than those in the Northern North Sea across all installation types, age ranges, and water depths. This translates to about 76% lower HCR incidents in the SNS compared with the NNS.[12]

4.2 Negative binomial model

We utilise the negative binomial model to control for the overdispersion and the inflated models to control for the excess zeroes. We start with the Poisson regression and add a multiplicative random effect to represent any unobserved heterogeneity as an approach to modelling the overdispersion. The expected value of the negative binomial model[13] is $E(Y_i|X_i) = \mu_i$ and variance $Var\,(Y_i|X_i) = \mu_i + \alpha{\mu_i}^2$. Thus, the expected value remains the same irrespective of the choice of distribution; however, the variance changes depending on the distribution utilised.

From Table 2, the results of the negative binomial (NB2) model show that the time trend is, as before, highly statistically significant (α=5%) suggesting an overall downward trend in HCR release incidents post the 1992 safety case regime and subsidiary regulations in line with expectation across the time trend and all three interaction models. There was a 3.6% overall decrease in the number of HCR incidents or a reduction of 0.96 releases per installation $[\,i.e.\,exp\,(-0.0362) = \ 0.9643]$ over the 17 year period from 1995 to 2011. The reference category for our indicator variables which in this case are fixed installations which are less than five years old situated in less than 100m of water in the Northern North Sea recorded a statistically significant value of 0.82 times less HCRs or a 56% overall reduction in HCRs in all five specifications.

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[11] It is important to note that the level of investments on these installations from 1995 to 2011 is not known as this remains confidential data of the operators.

[12] This follows from the fact that $1 - exp\,(-1.446) \ = \ 07645$

[13] The negative binomial fits two different parameterizations namely the mean and the constant dispersion models. The mean-dispersion or NB2 model characterized by Cameron and Trivedi (2010) is what we describe in equation 4.34 and used in our estimation. In the constant-dispersion or NB1 model the variance follows the order $Var\,(Y_i|X_i) = \mu_i(1 + \delta)$

Table 2 Incidence Rate Ratios (IRR) for Negative Binomial Model and Interaction Terms

Parameter	NB2 Time Trend Model	NB2 Time Trend & Oil Price	NB2 Time Trend, Oil Price & Production	Location and Age	Age and Installation Type	Age and Water Depth	Installation Type and Water Depth
β_1 Intercept	0.441* (0.101)	0.447* (0.096)	0.156 (0.214)	0.342* (0.114)	0.328* (0.087)	0.525* (0.125)	0.352* (0.083)
β_2 Time Trend	0.964* (0.015)	0.949 (0.029)	0.971 (0.044)	0.968* (0.014)	0.962* (0.014)	0.967* (0.015)	0.964* (0.015)
β_3 Oil Price	-	1.000 (0.006)	1.006 (0.08)	-	-	-	-
Installation Type:							
β_4 Mobile	0.979 (0.111)	0.981 (0.111)	0.980 (0.112)	0.929 (0.111)	1.599* (0.326)	0.962 (0.108)	1.508* (0.255)
Water Depth:							
β_5 >100m	2.119* (0.255)	2.110* (0.253)	2.110* (0.253)	2.245* (0.275)	2.333* (0.266)	1.367 (0.290)	2.837* (0.365)
Location:							
β_6 Central North Sea	2.501* (0.317)	2.491* (0.309)	2.494* (0.309)	3.445* (1.129)	2.645* (0.347)	2.513* (0.306)	2.639* (0.347)
β_7 Southern North Sea	0.569 (0.172)	0.564* (0.161)	0.566* (0.162)	0.648 (0.253)	0.622 (0.183)	0.578* (0.153)	0.679 (0.200)
Age:							
β_8 5-10 years	1.256 (0.183)	1.255 (0.182)	1.262 (0.182)	0.997 (0.3716)	1.162 (0.183)	1.112 (0.225)	1.249 (0.172)
β_9 10-15 years	1.641* (0.246)	1.635* (0.246)	1.650* (0.246)	1.945 (0.713)	1.848* (0.323)	1.040 (0.208)	1.685* (0.253)
β_{10} 15-20 years	1.765* (0.342)	1.759*(0.338)	1.767* (0.241)	2.511* (0.896)	2.927* (0.635)	1.486 (0.485)	1.779* (0.344)
β_{11} >20 years	1.202 (0.239)	1.204 (0.242)	1.209 (0.243)	1.640 (0.580)	1.733* (0.424)	0.834 (0.356)	1.216 (0.237)
Production							
β_{12}	-	-		-	-	-	-
Interaction Terms:							
A. Location and Age:							
CNS_5-10 yrs	-	-	-	1.391 (0.580)	-	-	-
CNS_10-15 years	-	-	-	0.830 (0.337)	-	-	-
CNS_15-20 years	-	-	-	0.448* (0.181)	-	-	-
CNS_>20yrs	-	-	-	0.504 (0.188)	-	-	-
SNS_5-10 yrs	-	-	-	1.035 (0.475)	-	-	-
SNS_10-15 years	-	-	-	0.642 (0.293)	-	-	-
SNS_15-20 years	-	-	-	1.463 (1.011)	-	-	-
SNS_>20yrs	-	-	-	1.049 (1.426)	-	-	-

B. Age and Installation Type:							
Mobile_5-10 yrs	-	-	-	-	1.186 (0.323)	-	-
Mobile_10-15 years	-	-	-	-	0.772 (0.222)	-	-
Mobile_15-20 years	-	-	-	-	0.096* (0.039)	-	-
Mobile_>20yrs	-	-	-	-	0.225* (0.094)	-	-
C. Age and Water Depth							
>100m_5-10 yrs	-	-	-	-	-	1.336 (0.379)	-
>100m _10-15 years	-	-	-	-	-	2.414* (0.669)	-
>100m _15-20 years	-	-	-	-	-	1.478 (0.543)	-
>100m _>20yrs	-	-	-	-	-	1.950 (0.960)	-
D. Installation Type-Water Depth							
Mobile_>100m	-	-	-	-	-	-	0.499* (0.106)
Dispersion parameter (α)	0.762	0.766	0.76	0.736	0.632	0.722	0.730
Residual d.f.	523	522	521	515	519	519	522
Log Likelihood	-1,323.91	-1,323.62	-1323.27	-1,310.21	-1,286.99	-1,318.35	-1,318.26
No. of observations	534	534	534	534	534	534	534
No. of zero-observations	486	486	486	486	486	486	486
Pseudo R^2	0.068	0.068	0.068	0.078	0.094	0.072	0.072

Absolute robust standard errors in brackets. *Significant at 5%. N = 534

IRR Estimates: The table reports IRR (incidence rate ratio) coefficients. Total number of platforms is used as the exposure term. Each coefficient is transformed into the IRR, whereby a coefficient of 1 indicates no change at all in predicted hydrocarbon releases; coefficients between 0 and 1 represent a predicted fall in releases (e.g. a coefficient of 0.88 represents a 12% decline); and coefficients greater than one represent predicted increases (e.g. a coefficient of 1.29 represents a 19% rise).

Regarding the location coefficients, facilities in the CNS region recorded a statistically significant 0.92 more HCRs compared to the NNS region for all age bands, installation type and water depth categories. This translates to 150% more HCRs $[exp\,(0.9169) = 2.501]$ than the NNS region installations with the same age band, installation type and water depth categories. SNS installations though not statistically significant, recorded 0.56 less (43% lower) HCRs than NNS installations across all installation types, age ranges, and water depths.[14] The installation type parameter was only statistically significant in the age-installation type interaction model.

Here, the positive sign on the installation type coefficient indicates that compared to fixed installations, mobile installations can be expected to have 60% more HCRs for each category of age band, installation, type and location. This result again deviates from our *ex-ante* expectation that comparatively, fixed installations would have had a higher probability on HCR incidents since most fixed installations in the UKCS relied on legacy infrastructure and were installed during the early operational years in the North Sea. It is again important to note that the level of investments made by operators on maintenance and reengineering works on these installations over the 17-year period from 1995 to 2011 is not known and thus not factored into the model (This is proprietary data). Also, HSE's inspection regime regarding how targeted inspections are carried out is also unknown at the time of this study.

The water range coefficient was statistically significant across all models except the age-water depth interaction. Across these models, installations that are situated in water depths greater than 100m have on average an extra 120% more HCRs for each category of age band, installation type, and location. With the exception of installations that are more than 20 years old, the age effect estimates show the number of HCRs increasing with the age of the installation irrespective of the location, installation type or the water depth in which the facility is in the UKCS. Compared to installations that are less than five years of age, 5 to 10-year-old installations were not statistically significant across all five models. On the other hand, 10 to 15-year-old installations were statistically significant in the time trend, time trend-oil price model as well as the age-installation type and installation type-water depth interaction models recorded 64%, 63%, 85% and 68% more HCRs respectively.

This result though not surprising, partly confirms our *a priori* expectation that *ceteris paribus*, accidents and hydrocarbon spills are more likely to occur on older platforms and installations than they would on relatively newer ones because of technological factors (barriers) employed in the detection and control of HCRs in line with the continuous reduction of major accident hazards under the ALARP principle. Most of the interaction terms in the model were not statistically significant. A summary comparison of the Poisson and Negative Binomial Models is presented in Table 3 below.

[14] This was significant at the 10% level for the base model. This follows from the fact that $1 - exp\,(-0.5633) = 07645$

Table 3 Comparison of Base Poisson and Negative Binomial Models [IRR]		
Parameter	**Base Poisson Model**	**Base NB2 Model**
β_1 Intercept	**0.861** (0.143)	**0.441*** (0.101)
β_2 Time Trend	**0.968*** (0.007)	**0.964*** (0.015)
β_3 Oil Price	-	-
Installation Type:		
β_4 Mobile	**1.079** (0.108)	**0.979** (0.111)
Water Depth:		
β_5 >100m	**1.702*** (0.157)	**2.119*** (0.255)
Location:		
β_6 Central North Sea	**1.397*** (0.136)	**2.501*** (0.317)
β_7 Southern North Sea	**0.235*** (0.035)	**0.569** (0.172)
Age:		
β_8 5-10 years	**1.147** (0.141)	**1.256** (0.183)
β_9 10-15 years	**1.378*** (0.178)	**1.641*** (0.246)
β_{10} 15-20 years	**1.409*** (0.181)	**1.765*** (0.342)
β_{11} >20 years	**1.088** (0.123)	**1.202** (0.239)
Pseudo R^2	0.45	0.07
Dispersion parameter (α)	3.84	0.76
AIC	3,377	2,670
Residual d.f.	525	525
Log Likelihood	-1,678.38	-1,323.91
No. of observations	534	534
No. of zero-observations	486	486

Absolute robust standard errors in brackets. *Significant at 5%
IRR Estimates: The table reports IRR (incidence rate ratio) coefficients. Total number of platforms is used as the exposure term. Each coefficient is transformed into the IRR, whereby a coefficient of 1 indicates no change at all in predicted hydrocarbon releases; coefficients between 0 and 1 represent a predicted fall in releases (e.g. a coefficient of 0.88 represents a 12% decline); and coefficients greater than one represent predicted increases (e.g. a coefficient of 1.29 represents a 19% rise).

4.3 Average marginal effects

Table 4 below shows the results of the average marginal effects of our negative binomial model. The margin for the time trend was -0.18 and -0.21 in the Poisson and negative binomial models, respectively. This translates to a statistically significant 21% reduction in HCRs from 1995 to 2011 in the negative binomial case, other things being equal after controlling for location, water depth, installation type, and installation age.[15]

Facilities located in the CNS region had, on average, a statistically significant five more HCRs than NNS installations under the negative binomial model compared to two under the Poisson case. SNS installations had three fewer HCR releases than NNS installations (8 more releases under the Poisson case), all other things being equal.

On the water range, facilities located in more than 100m of water recorded on average four more HCRs than those in less than 100m of water in line with our *a priori* expectation of increased water depth affecting the probability of an HCR occurrence. This was three more releases under the Poisson model and was statistically significant as well.

Mobile installations recorded more marginal average reduction HCRs than fixed installations, all other things being equal under the negative binomial case. This was not statistically significant,

[15] See appendix for parameter estimates and standard errors

though it falls in line with our *a priori* expectation of technological advancements on mobile installations having newer production technologies such as logic systems that prevent and/or control the release of hydrocarbons being much better than the legacy infrastructure on most fixed installations in the UKCS.

With regard to the age of the installations, those in the 10 to 15 and 15 to 20-year band recorded a statistically significant average increment in HCRs of 2 and 3 more releases under the Poisson and negative binomial models respectively. Installations in the 5-10 and greater than 20-year age bands were not statistically significant at the 5% level for all models. Again, we did not observe any incremental changes in HCRs as the installations moved onto different age bands over the 17 years under both models.

Also, we tested for the marginal effects across different categories of our covariates controlling for individual specific items. These are the installation type-age effects and the installation type-location effects. Given that water range, installation type and some age bands are significant in the overall model; we tested for the marginal effect at the representative value for mobile installations, water depth (>100m) and 0 to 15 and 15 to 20-year age bands respectively. For mobile installations in water depths greater than 100m, and in the 10 to 15-year age cohort, our results from the negative binomial model show similar statistically significant reductions for the time trend, but a marginal increase in HCRs for 15 to 20-year-old installations from 3 to 4 releases.

Table 4 Average Marginal Effects of the Poisson and Negative Binomial Time Trend Models

Parameter	**Time Trend Poisson Model dy/dx (Std. Err)**	**Time Trend + Oil Price Poisson Model dy/dx (Std. Err)**	**Time Trend NB Model dy/dx (Std. Err)**	**Time Trend + Oil Price NB Model dy/dx (Std. Err)**
β_2 Time Trend	**-0.178*** (0.042)	**-0.044** (0.096)	**-0.209*** (0.087)	**-0.299** (0.195)
β_3 Oil Price	-	**-0.027** (0.018)	-	**0.017** (0.040)
β_4 Mobile	**0.428** (0.565)	**0.426** (0.563)	**-0.119** (0.660)	**-0.105** (0.659)
β_5 >100m	**2.977*** (0.510)	**2.980*** (0.505)	**4.347*** (0.809)	**4.325*** (0.790)
β_6 Central North Sea	**1.870*** (0.524)	**1.871*** (0.513)	**5.304*** (0.953)	**5.285** (0.928)
β_7 Southern North Sea	**-8.094*** (0.976)	**-8.091*** (0.960)	**-3.259** (1.580)	**-3.314** (1.485)
β_8 5-10 years	**0.767** (0.687)	**0.704** (0.694)	**1.321** (0.848)	**1.318** (0.848)
β_9 10-15 years	**1.796*** (0.728)	**1.823*** (0.721)	**2.866*** (0.908)	**2.848*** (0.906)
β_{10} 15-20 years	**1.919*** (0.723)	**1.974*** (0.713)	**3.289*** (1.195)	**3.271*** (1.182)
β_{11} >20 years	**0.476** (0.637)	**0.452** (0.628)	**1.066** (1.204)	**1.077** (1.219)

5 Conclusion and Policy Implications

Industry practitioners, as well as the regulator, accept that hydrocarbon releases (HCRs) remain a key indicator of how well the offshore industry is managing major hazard risks and the integrity of installations. Descriptive statistics of the figures indicate that HCRs have gradually been on the decline over the past decade. For example, in the years following the passage of the 1992 regulations, major releases have consistently declined year-on-year from an average of 19 releases in 1997/98 to 3.6 releases in 2011/2012.

However, these comparative statistics and simple metrics may be distorted or compounded by other factors. Thus, to help understand the underlying dynamics, we used multivariate regression analysis based on the generalized linear modelling framework to provide a more comprehensive interrogation of the determinants of hydrocarbon releases in the UKCS post the 1992 and ancillary regime changes with a view to empirically ascertain the trend, if any, of how the safety case regime change has helped in controlling major offshore accident hazard risks. This research answers some of the policy questions around offshore safety economics issues that an upstream regulator could adopt to guide the formulation of strategies to maximise economic recovery in the UKCS.

We estimated Poisson and Negative Binomial type generalised linear models to analyse the determinants of HCRs in the UKCS. Using the Poisson and Negative Binomial models to analyse HCRs standardised by the installation count, the statistical evidence shows that there was a reduction in HCR incidents with a 3.2% year-on-year decrease in the number of release occurrences after controlling for other model parameters. This reduction coincides with the period that the Safety Case Regulations were vigorously enforced. The other model parameters such as the location of offshore facilities, production type and water depth were also statistically significant in determining the probability of the occurrence of a hydrocarbon release in the UKCS.

The data show an industry-wide decline in hydrocarbon releases over the past two decades, which reflects both the commitment of operating companies and the regulator to reduce major accident hazards in line with the principles underlying the Safety Case regime. This improvement is reflected in various anecdotal and qualitative evidence from industry bodies and forums such as Oil and Gas UK and Step Change in Safety, which continue to push for even more reduction of HCRs. Evidently, reducing the number of HCRs requires the regulator to require improved performance in the production and processing of hydrocarbons by preventing uncontrolled releases through a risk-based assessment of major accident hazards. This calls for a more nuanced risk-based approach to offshore safety.

The study makes two policy recommendations on the offshore safety regime in the UKCS. First, the regulator should continue to focus its major accident reduction efforts predicated on the safety case regulations which identifies the key safety-critical elements of an oil and gas installation. Our findings on hydrocarbon releases, relative to the existing safety regime, leads us to believe that the correct identification of safety-critical elements on offshore installations as required by the safety case regulations will have a lasting positive impact on the control of hydrocarbon releases. Secondly, the regulatory focus must shift to understanding the dynamics of the releases in the Central North Sea Region as it has on average more releases that are statistically significant compared to other regions This also applies to the case of fixed installations in the UKCS given that mobile installations recorded more marginal average reduction releases than fixed installations. Regarding the age of the installations, we recommend focused attention on those in the 10 to 15 and 15 to 20-year band (the post-CRINE era installations) as they recorded statistically significant increments in hydrocarbon releases relative to even the older platforms over 20-years in age.

Future work could consider other proxies to capture the economic incentives in the context of potential omitted variables. For example, oil prices could be supplemented by a cyclical cost parameter such as rig rates on the basis that it is net profits that incentivises companies. We did not immediately have access to historical rig rates in the industry, more so those which are specifically suited to the North Sea. Thus, it was impossible to model this parameter although we agree that a cyclical cost parameter might be useful one to include, even with possible lags. Future work could include these parameters in the regression models, and also use an expanded post-2011 dataset.

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