fire

Review

Fire Hazards Caused by Equipment Used in Offshore Oil and Gas Operations: Prescriptive vs. Goal-Oriented Legislation

Dejan Brkić [1,2,3]

[1] Faculty of Electronic Engineering, University of Niš, 18000 Niš, Serbia; dejan.brkic@elfak.ni.ac.rs
[2] IT4Innovations, VSB—Technical University of Ostrava, 708 00 Ostrava, Czech Republic; dejan.brkic@vsb.cz
[3] University of Belgrade, 11000 Beograd, Serbia; dejanrgf@tesla.rcub.bg.ac.rs

Abstract: This article offers a concise overview of the best practices for safety in offshore oil and gas operations, focusing on the risks associated with various types of equipment, particularly on the risk of fire. It identifies specific machinery and systems that could pose hazards, assesses their potential impact on safety, and explores conditions that may lead to accidents. Some of the largest accidents were analyzed for their associations with fire hazards and specific equipment. Two primary regulatory approaches to offshore safety are examined: the prescriptive approach in the United States (US) and the goal-oriented approach in Europe. The prescriptive approach mandates strict compliance with specific regulations, while in the goal-oriented approach a failure to adhere to recognized best practices can result in legal accountability for negligence, especially concerning human life and environmental protection. This article also reviews achievements in safety through the efforts of regulatory authorities, industry collaborations, technical standards, and risk assessments, with particular attention given to the status of Mobile Offshore Drilling Units (MODUs). Contrary to common belief, the most frequent types of accidents are not those involving a fire/explosion caused by the failure of the Blowout Preventer (BOP) after a well problem has already started. Following analysis, it can be concluded that the most frequent type of accident typically occurs without fire and is due to material fatigue. This can result in the collapse of the facility, capsizing of the platform, and loss of buoyancy of mobile units, particularly in bad weather or during towing operations. It cannot be concluded that accidents can be more efficiently prevented under a specific type of safety regime, whether prescriptive or goal-oriented.

Keywords: offshore safety; oil and gas industry; drilling technology; fire protection; marine pollution; safety regulations; risk assessment; technological innovations; best practices; prescriptive vs. goal-oriented approach

Academic Editors: Tiago Miguel Ferreira and Lizhong Yang

Received: 15 November 2024
Revised: 16 December 2024
Accepted: 13 January 2025
Published: 16 January 2025

Citation: Brkić, D. Fire Hazards Caused by Equipment Used in Offshore Oil and Gas Operations: Prescriptive vs. Goal-Oriented Legislation. *Fire* **2025**, *8*, 29. https://doi.org/10.3390/fire8010029

1. Introduction

Large offshore oil spills and accidents can disrupt the economy of an entire region, damaging fisheries and critical habitats [1,2]. Additionally, workers and personnel on board the offshore drilling or exploitation facility can be injured [3,4]. Such accidents may involve fire as either a source or a consequence, but they can also occur without any fire at all [5]. In most cases, explosions are commonly linked to the presence of fire [6]. The devices and equipment used in the offshore oil and gas industry are highly advanced and sophisticated, but under certain circumstances they can be the source of or can be involved in accidents, some of them more frequently than others. The causes can be various, originating from different types of installed equipment [7].

It is evident that devices and equipment for the offshore oil and gas industry are manufactured in various countries, likely adhering to different technical standards. It is foreseeable that such equipment, once installed on drilling units and occasionally on exploitation platforms, will be transferred among countries during their operational lifespans. The offshore oil and gas industry operates on a range of overlapping philosophies, each employing a different approach to ensuring high levels of safety. Similar to nuclear accidents, large offshore accidents are not frequent, but if they do occur, the consequences could be enormous [8–10].

To prevent accidents, the development of new, stricter regulations for the offshore oil and gas industry and the restructuring of regulatory authorities should be a continuous effort. In addition, national and international authorities, along with industrial associations, should collaborate to develop better safety technologies and standards, as well as promote safer operational practices at offshore facilities, especially considering that pollution does not recognize national borders. Most recommendations are focused specifically regarding detailed standards and guidelines for well control and emergency response, the role of the regulator, the necessary competencies and training, preparedness for emergency response, safety management [11], and workforce engagement. All evaluations in this article are through the two different approaches in offshore safety [12,13]:

1. Prescriptive—used in the United States (US);
2. Goal-oriented—used in Europe (European Union, Norway, UK, etc., but not in Russia, where the prescriptive approach is used).

Accidents and their possible association with specific equipment and with fire occurrence were analyzed. Typical failures on offshore units may include insufficient details in procedures, inadequate hazard identification, particularly concerning risks from well design, a delayed response to early warning signals, poor communication, unclear leadership and responsibility, an inability to learn from past accidents and near misses, and inadequate personnel training, especially in handling emergency situations. This paper also analyzes if accidents are more frequent in prescriptive or in goal-oriented safety regimes.

This article is structured as follows:

1. Section 1 presents introductory notes;
2. Section 2 examines the current state of offshore safety, including specific safety issues related to Mobile Offshore Drilling Units (MODUs) [14,15];
3. Section 3 addresses the main categories of equipment used in the offshore oil and gas industry, with identification of their potential connection with accidents;
4. Section 4 gives conclusions.

While this article is far from complete or exhaustive, it should also provide a concise overview of the areas where work is ongoing and where significant developments are taking place. The comparison highlights how prescriptive approaches focus on specific rules to ensure safety, while goal-oriented approaches emphasize achieving safety outcomes through flexibility and innovation. This distinction helps identify which method better addresses the complex, evolving risks in offshore oil and gas operations. Ultimately, understanding their strengths and limitations supports the development of balanced safety strategies that enhance overall risk management.

2. Current State of Offshore Safety

This analysis includes recent legislative advancements, improved procedures, innovative technological designs, organizational frameworks, and efforts toward standardization that can prevent accidents.

The two main approaches in enhancing overall levels of offshore safety are (1) prescriptive and (2) goal-oriented.

1. Prescriptive legislation specifies detailed rules and procedures that must be followed. It dictates how something must be done and is typically very specific and detailed. This approach leaves little space for interpretation or flexibility and provides clear instructions for compliance. The prescriptive approach emphasizes strict compliance with predetermined regulations rather than allowing flexibility in safety practices [16]. The advantages include ensured consistency and uniformity, reduced ambiguity (which facilitates enforcement), and certainty for regulated entities. However, the disadvantages include inflexibility, the potential to stifle innovation, and the risk of becoming outdated as technology or circumstances change. Additionally, prescriptive legislation often requires frequent updates to adapt to new developments. This type of legislation works well when a uniform approach is necessary and safety or predictability is critical. The prescriptive approach is mandatory in the US for offshore oil and gas operations.
2. Goal-oriented legislation sets out the outcomes that need to be achieved but allows flexibility in how these goals are met. It focuses on what needs to be accomplished rather than how to do it. This approach is broader and less detailed, encourages creative and adaptable solutions, and shifts the focus to achieving results rather than strictly following processes. The advantages of this approach include greater adaptability to changing conditions or technologies and a reduced need for frequent amendments. However, the disadvantages include greater ambiguity, which can lead to inconsistent interpretations, and more complex compliance assessments. In the goal-oriented approach used in Europe [17,18], failure to comply with widely recognized and reasonable best practices for safety in the offshore oil and gas sector is considered negligent (tort law). As a result, those responsible are held fully accountable for the loss of human lives and environmental damage caused by such negligence.

Examples of prescriptive legislation can include building codes, food safety regulations, financial reporting requirements, etc. On the other hand, examples of goal-oriented legislation may include environmental regulations that set prescribed goals without specifying the exact means to achieve them, such as stating, e.g., "reduce carbon dioxide emissions by 40% by 2030" without prescribing exact measures. Another example can be data protection legislation, which aims to ensure personal data are handled securely and with user consent but does not dictate the specific technical measures to be taken. This allows companies to adopt their own strategies, provided they meet the goals of data security and privacy.

Offshore oil and gas safety can be assured using both prescriptive and goal-oriented legislation. Prescriptive legislation is commonly used in the United States and prevails in countries such as Russia, China, India, Iran, Egypt, Thailand, Qatar, Saudi Arabia, etc. while goal-oriented legislation is more prevalent in the European Union, Brazil, Mexico, Australia, etc.

With regard to offshore oil and gas safety, particular attention is given to (i) national legislation; (ii) guidelines of industry associations; (iii) safety technologies, with emphasis on key advancements, particularly in well integrity [19], Blowout Preventers (BOP), and capping and containment stacks; and (iv) technical and operational standards [20].

2.1. National Legislation

There are two main approaches in the offshore safety worldwide [21]: prescriptive, used in the United States (US), and goal-oriented, used in Europe.

The US regulations, practices, and technical standards are not only acceptable in Europe but are also mandatory in the European offshore industry. Europe's goal-oriented approach mandates the use of the best available global technologies and practices, where the US industry is recognized as one of the most advanced. It is often more cost-effective to follow only one approach, especially when offshore operations move frequently from US to European jurisdictions and vice versa, as is the case with Mobile Offshore Drilling Units (MODUs). However, the European goal-oriented philosophy integrates the best practices from the US approach and enhances overall safety levels through specifically tailored safety cases for each facility [22].

Currently as a specific circumstance, in waters of the European Union, certain exclusions from European legislation apply. Some provisions of EU safety directives, such as the ATEX Directive 2014/34/EU, the Pressure Equipment Directive 2014/68/EU, and the Machinery Directive 2006/42/EC, which are applicable onshore, have limited applicability offshore and differ in their application to offshore platforms and mobile units:

1. They only cover equipment installed on fixed platforms used for offshore oil and gas exploitation;
2. Drilling equipment on board Mobile Offshore Drilling Units (MODUs) and drilling operations fall outside their scope.

However, both fixed platforms and MODUs in Europe must comply with the provisions of Directive 2013/30/EU, which serves as the overarching framework for offshore safety in Europe. The stability of MODUs and general navigation purposes are governed by the IMO MODU Code (A 26/Res. 1023), which treats them as ships and applies in both the US and Europe. In general, MODUs use IECEx protection against explosions [5,23–25].

To determine which offshore vessels the described exclusions of EU safety directives apply to, it is important to note that MODUs can be defined as submersibles, jack-ups, semisubmersibles, and drill ships, each with its own description [26]. Mobile units also include various deepwater systems, such as compliant towers, floating production, storage, and offloading (FPSO) vessels, floating storage offloading systems, semisubmersibles, tension leg platforms (TLPs), deep draft column vessels (spars), various subsea systems, etc. [26].

2.1.1. United States (US): Prescriptive Approach

The foundational law for offshore oil and gas activities in the US is the Outer Continental Shelf Lands Act (OCSLA) from 1953, which has been amended several times since then. The enforcement falls under the US Department of the Interior (DOI), which de facto renamed the Mineral Management Service (MMS) and eventually the Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE), which was reorganized into three independent agencies in 2010, namely:

1. The Bureau of Safety and Environmental Enforcement (BSEE), which is responsible for collecting and disbursing revenues from energy production;
2. The Bureau of Ocean Energy Management (BOEM), which is responsible for the management and development of offshore resources in an environmentally and economically responsible way;
3. The Office of Natural Resources Revenue (ONRR), which is responsible for the enforcement of safety and environmental regulations.

The purpose of such a restructuring was to separate and assign clear roles and responsibilities, while safety remains under jurisdiction of the BSEE.

The US follows a prescriptive regulatory framework, where companies must comply with specific safety rules and standards set out in regulations, namely in the Safety and Environmental Management Systems (SEMS) rule [27]. In addition, environmental assessments of offshore oil and gas projects are supported by the National Environmental Policy Act (NEPA) [28], while workplace safety is overseen by the Occupational Safety and Health Administration (OSHA) [29].

In the 1990s, the BSEE issued the Workplace Safety Rule, requiring offshore oil and gas operators to develop and maintain a Safety and Environmental Management System (SEMS) based on the Code of Federal Regulations (CFR): Title 30, Chapter II, Subchapter B, Part 250, Subpart S. This rule sets safety and environmental standards for offshore oil and gas operations, focusing on risk management and safety practices as outlined in the American Petroleum Institute (API) RP 75, where RP stands for Recommended Practice. The rule, updated in 2011 and informally referred to as SEMS II [30], requires a third-party audit [31] and is largely non-prescriptive, meaning it does not provide detailed guidance on specific actions that offshore operators should take. The general tendency is that the US approach is moving towards the European-style safety case regime [32,33]. To support implementation, the US government issued numerous Notices to Lessees (NTLs) as additional guidance to operators on how to comply with regulations, including guidelines for Blowout Preventers (BOPs) and well control operations.

In the US, unlike in Europe, regulators do not formally assess or approve safety cases for offshore oil and gas operations due to concerns about liability in the event of accidents. The Bureau of Safety and Environmental Enforcement (BSEE), as the US regulator, does not audit safety cases as they are not required to do so in the US regulatory framework. Instead, companies must conduct SEMS audits, which are reviewed by the regulator. While European regulators use a safety case regime—where operators develop comprehensive safety plans that must be approved—the US focuses on enforcing compliance with specific regulations. In Europe, operators are held to the As Low as Reasonably Practicable (ALARP) approach, encouraging continuous safety improvement, but this concept does not exist in the US. The lack of an ALARP framework in the US makes it harder to adopt a safety case regime and leads to disputes over regulatory interpretation.

Although not regulatory, standards by the American Petroleum Institute (API) are widely adopted in the US and international industry for safe and efficient operations [34] (for example, the obligatory SEMS rule can be enforced through the application of API RP 75 [35] and the SEMS rule takes precedence if there are potential conflicts between these two documents).

2.1.2. Europe: Goal-Oriented Approach

The European system follows a goal-oriented approach, requiring operators to demonstrate the implementation of effective safety measures. It is governed by the Directive 2013/30/EU, which serves as the framework for offshore safety in European waters. It was introduced in response to the Deepwater Horizon disaster in 2010 [36–39] to ensure that such accidents are prevented in European waters and that operators are better prepared to handle potential emergencies. The Norwegian safety model [40–43] was indeed a key influence, particularly in promoting a goal-oriented and risk-based regulatory framework, that inspired the Directive 2013/30/EU.

Key points of the Directive 2013/30/EU include the following:

1. Goal-Oriented Safety: Operators are required to submit a comprehensive safety case for each offshore installation demonstrating how they manage risks and ensure safe operations. One of the fundamental shifts after the public inquiry into the Piper Alpha disaster of 1988, in which 167 workers lost their lives on a North Sea oil platform, was the introduction of a safety case regime [44]. A safety case is a comprehensive document that outlines how a company manages safety risks, providing detailed risk assessments, safety management systems, and control measures to ensure safe

operation. This shifted the responsibility for ensuring safe practices from regulatory authorities to the operators themselves, making them responsible for demonstrating how they would manage risks.

2. Environmental Protections: The Directive 2013/30/EU emphasizes environmental safeguards, ensuring that operators are responsible not only for safety but also for preventing and mitigating environmental damage from offshore activities [45].
3. Independent Competent Authorities: An independent competent authority should be designated to oversee the enforcement of the Directive 2013/30/EU, ensuring strict and unbiased regulation. For example, the competent authority in Norway is the Petroleum Safety Authority (PSA/PTIL).
4. Transparency and Reporting: Operators must report major accidents and near misses using a common reporting format, with the information made publicly available to promote transparency and improve safety standards across the industry.
5. Liability and Financial Security: Companies must demonstrate they have sufficient financial resources to cover liabilities in the event of a major accident, ensuring they can respond effectively to accidents.

While US regulations can serve as a reference or inspiration, they cannot be directly used to comply with the Directive 2013/30/EU. However, operators may still apply certain US practices or standards as long as they align with or exceed the safety and environmental requirements outlined by the Directive; While the Directive 2013/30/EU mandates a tailored safety case, companies should incorporate best practices and technologies from around the world, including the US, as long as these practices meet or exceed European safety and environmental protection standards. Operators can draw on US regulations as a part of their safety cases, but these must be adapted to fit the risk-based and goal-oriented nature of the Directive. Some standards used in the US, such as those from the American Petroleum Institute (API), may be accepted in Europe if they effectively support the safety case by demonstrating that risks have been identified and appropriate measures have been implemented, tailored to specific installations.

2.2. Guidelines of Industry Associations

Industry associations play a crucial role in enhancing offshore oil and gas safety by setting standards, facilitating collaboration, and providing training and certification. They help drive continuous improvement in safety practices, contributing to a safer and more sustainable offshore environment. Over the years, numerous international and industry associations have been highly active, with their often collaborative efforts leading to the creation of technical and working groups. These groups have made valuable contributions to improving offshore safety standards, identifying and sharing best practices, and advancing new safety technologies.

While there are others, the most important working groups in the offshore sector which operate globally are as follows:

1. International Association of Oil and Gas Producers (IOGP): Develops global safety standards and promotes risk management and best practices; although it advocates a goal-oriented approach, its standards and best practices are globally applicable, influencing both US and European safety cultures. It produces Standards and Guidelines in the field of life-saving, environmental performance, safety indicators, global standards on well control, etc.
2. Offshore Petroleum Industry Training Organization (OPITO): Sets global standards for offshore safety training and workforce competency relevant for both the US and European approach. It offers “Basic Offshore Safety Induction and Emergency

Training (BOSIET)" covering crucial safety elements such as helicopter safety and escape, sea survival, firefighting and self-rescue, basic first aid, etc.

The prescriptive, i.e., US, approach is supported by the following:

1. American Petroleum Institute (API): Widely used in the US and beyond, it promotes a prescriptive approach with detailed technical standards for well integrity, blowout prevention, and equipment safety.
2. Center for Offshore Safety (COS): Promotes safety management systems and shares safety performance data, especially in the Gulf of Mexico, promoting prescriptive regulations and performance tracking. It supports enforcement of the SEMS rule through various guidelines for SEMS requirements, audit protocols, guidance on leadership and culture, risk management, operational safety, etc.
3. International Association of Drilling Contractors (IADC): Improves drilling safety through standards for well control and accident prevention. Its "Drilling Manual", a critical technical reference for ensuring safe and efficient drilling operations worldwide, provides comprehensive technical guidance, best practices for drilling operations, safety and environmental considerations, well control and equipment standards, training and certification guidelines, etc.

The goal-oriented and risk-based, i.e., European, approach is supported by the following:

1. International Marine Contractors Association (IMCA): Focuses on marine operations safety, including oil and gas exploration and production. Its guidance on safe system of work supports compliance efforts and contributes to safe offshore and subsea operations.
2. Step Change in Safety: Enhances North Sea safety through guidance, collaboration, and initiatives. Its "Life-Saving Rules" contributes to reducing accidents and enhancing the safety culture in the offshore oil and gas industry.
3. European Union Offshore Oil and Gas Authorities Group (EUOAG): Coordinates offshore safety practices among EU regulators under the Directive 2013/30/EU.
4. Norwegian Oil and Gas Association: Collaborates closely with regulators like the Petroleum Safety Authority (PSA/PTIL) and in the development and maintenance of NORSOK standards [46].

2.3. Safety Technologies

The most recent technical advancements in offshore accident prevention focus on Blowout Preventers (BOPs), while improvements in containment devices are centered around capping stacks. In the US, BOPs are regulated with the Code of Federal Regulations (CFR): Title 30, Chapter II, Subchapter B, Part 250, Sub-part G, which is in practice applicable in the European safety-case regime.

2.3.1. Blowout Preventers—BOPs

A Blowout Preventer (BOP) is a crucial safety device used in oil and gas drilling operations to prevent uncontrolled releases of crude oil or natural gas during drilling or exploitation, commonly known as a blowout. BOPs are installed at the wellhead and are designed to seal, control, and monitor oil and gas wells. They are designed to seal the wellbore if there is a sudden increase in pressure and to contain it for an extensive period of time. An annular preventer seals the well around various pipe sizes, whereas a ram preventer seals the well by either closing the wellbore or cutting the drill pipe [47–51].

Blowout Preventer (BOP) System Requirements are practically explained in API 16A for BOPs and API 17D for subsea production systems. A major revision of the requirements was done in 2016 and after that they have been revisited regularly (last in 2023):

- More Robust BOPs: BOPs were required to have the capacity to cut through pipe under extreme conditions (increased shear ram requirements).
- Real-Time Monitoring: Operators were required to monitor well conditions in real-time and have continuous access to BOP data.
- Dual Shear Rams: The use of dual shear rams was mandated to provide redundancy.
- Third-Party Certification: BOPs and well control systems had to be certified by independent third parties to ensure proper functionality.

In addition, subsea BOPs require a backup control system.

The last revision from 2023, among other changes, requires that surface BOPs on existing floating platforms must comply with dual shear ram requirements, while Remotely Operated Vehicles (ROVs) must be capable of operating each shear ram on subsea BOPs.

Europe mostly relies on US regulations. In addition, Norwegian NORSOK D-001 [52] requires that BOPs and associated equipment undergo both pressure testing and overhauls at regular intervals to ensure their proper functioning, wherein BOPs must be pressure-tested and maintained every five years to maintain their integrity. According to NORSOK D-010 [53], the BOP can be considered a well barrier element ensuring safety and well control during critical phases of operation (two independent well barriers must exist without sharing elements [54–58]), as can be seen in Figure 1.

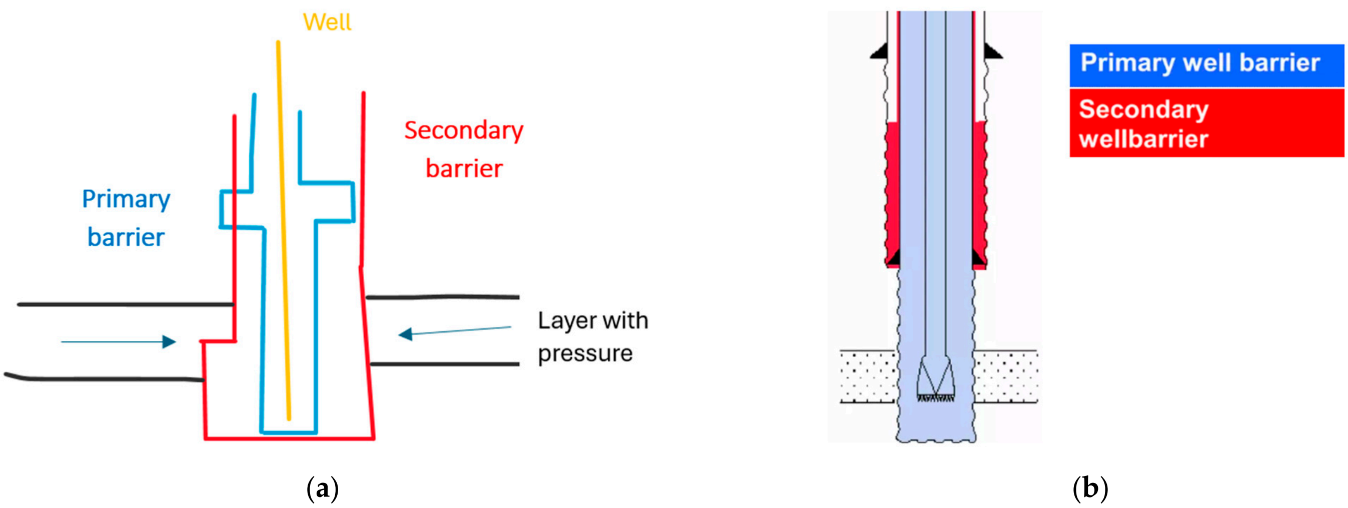

Figure 1. NORSOK D-010 concept of two independent well barriers: (**a**) Conceptual sketch and (**b**) an example from real engineering practice.

2.3.2. Capping Stacks

A capping stack is a specialized tool designed to seal a subsea well after a blowout, effectively stopping the uncontrolled release of oil or gas [59]. Once deployed over the damaged wellhead, it caps the well to halt the flow of hydrocarbons. The stack performs three critical functions: it seals the well to stop the flow, contains pressure within the well to prevent further leaks, and enables controlled interventions, either to permanently seal the well or resume operations safely.

Capping stacks are a crucial part of offshore emergency response plans, especially in deepwater drilling environments, where rapid well control is vital to preventing environmental disasters.

These devices are typically massive, weighing between 50 to 100 tons, and are placed over the wellhead. The first capping stacks, designed to contain and seal subsea blowouts, were developed in response to the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, with significant advancements since then.

Examples include devices developed by the Subsea Well Response Project (SWRP), available in Europe, Brazil, South Africa, and Singapore; the Marine Well Containment Company (MWCC) in the Gulf of Mexico; the Norwegian Clean Seas Association for Operating Companies (NOFO) in Norway; the Offset Installation Equipment (OIE) in Italy, etc. These devices are strategically located worldwide for quick deployment. The OIE, for instance, allows capping operations even when direct vertical access to the wellhead is not possible, making it ideal for complex scenarios.

Clean-up efforts after oil and gas spills are not only financially burdensome but also have profound environmental consequences [60,61]. The costs of such operations often include containment, removal, and remediation, which require specialized equipment, extensive labor, and long-term monitoring. Beyond the financial impact, spills can cause severe and sometimes irreversible damage to ecosystems, affecting marine and terrestrial habitats, harming wildlife, and disrupting local communities. The recovery of affected ecosystems is often slow, with lasting effects on biodiversity, water quality, and soil health. These challenges underscore the critical need for robust preventative measures and efficient response strategies.

2.4. Technical and Operational Standards

Technical standards in the offshore oil and gas industry are crucial for ensuring the safety of personnel, protecting the environment, and maintaining the structural integrity and reliability of equipment and facilities. More information about the relationship among standardization bodies and their roles in various legal offshore jurisdictions can be found in [6,62].

Examples of the most important are the American Petroleum Institute (API) from the US and the Norwegian NORSOK. The API and NORSOK play crucial roles in the offshore oil and gas industry, especially in setting technical and safety standards. However, their focus is on slightly different areas and regions.

2.4.1. US American Petroleum Institute (API) Standards

API standards are primarily used in the US, where they are developed and referenced by US authorities. However, these standards are often applied in Europe, where the use of all best practices available worldwide is required to support safety cases under the Directive 2013/30/EU. When operating in European waters, compliance with the best available safety standards is essential, whether they are developed in Europe or internationally. The only requirement is that there are no conflicts with regional regulations.

2.4.2. Norwegian NORSOK Standards

NORSOK standards can be used in the US, but their adoption is less common compared to API standards. Primarily developed for Norway's offshore oil and gas industry, NORSOK standards focus on the harsh North Sea environment, ensuring safety, cost-efficiency, and high performance. While internationally recognized, NORSOK standards are not directly referenced by US regulations in the same way as API standards.

For example, there is not a direct API standard that completely replaces NORSOK D-010, which is widely regarded as the leading standard for well integrity in the offshore oil and gas industry. NORSOK D-010 covers the entire lifecycle of well operations, including drilling, completion, and abandonment, with a strong emphasis on safety and well barriers. In NORSOK D-010, two independent well barriers are required to ensure well integrity [54–58], as shown in Figure 1:

1. Primary Barrier: The main pressure-containment system, typically including casing and wellhead equipment;

2. Secondary Barrier: An additional system, like Blowout Preventers (BOPs), that acts if the primary barrier fails.

3. Accidents and Equipment

This Section presents an inventory of the main equipment used in offshore oil and gas operations. The purpose of this inventory is to identify whether certain pieces of examined equipment were involved in the largest offshore oil and gas accidents. The analysis also includes a comparison of accidents involving fire and those without to determine if the same equipment and causes can be linked to both types. Additionally, this assessment investigates the proportion of accidents that occur under different legislative jurisdictions, specifically those with prescriptive versus goal-oriented regulatory approaches. Finally, the analysis examines where accidents resulting in a higher number of casualties most commonly occur and whether these accidents take place on drilling or production facilities and on mobile or fixed platforms [63].

3.1. Categories of Equipment

The variety of equipment used in the offshore oil and gas industry is vast, so for the purposes of this study, it is more practical to focus on systems or groups of equipment rather than individual devices.

The here-defined categories were created solely to simplify information management and are not intended to be definitive classifications for identifying equipment that could be a source of a major offshore accident, especially with those involving fire and/or explosions. For each system or group of equipment, it is evaluated whether it could be present in explosive atmosphere and under what conditions. If so, each piece of equipment is assessed as a potential ignition source, determining whether its moving parts could generate sparks (and, for electrical equipment, sparking caused by discharge), whether it may be subject to pressure, or whether it can experience increased temperatures.

This study deals mainly with identifying specific systems or equipment that may pose fire hazards and understanding the conditions that could lead to large accidents. In addition, as given by Vinnem [64], hazards can be due dropped objects, ballast system failure, anchor line failure, loss of buoyancy, accidental weight conditions, accidents during towing, etc. Additionally, safety factors connected with equipment system risk in downstream oil and gas industry are identified by Waqar et al. [65] as explosion or leakage by using the wrong equipment, crane failures, being caught in or struck by running equipment, faulty digital data-monitoring equipment, and the failure of hydraulic equipment on site. The obsolescence of equipment also can be a source of failure in the offshore industry [66,67].

The goal is to prevent serious accidents by identifying hazardous elements, while the practical risk assessment is based on the analysis of past accidents, i.e., on the evaluation of the likelihood that a specific element could have a greater impact in an undesired scenario.

Six main categories (with partial overlap) are selected by grouping certain equipment for the purpose of identifying hazard from fire and/or explosions (for the purpose of this study, a code is assigned to each group as follows):

1. Drilling equipment (Code I)—Table 1;
2. Well intervention equipment (Code II)—Table 2;
3. Material handling equipment (Code III)—Table 3;
4. Well control equipment (Code IV)—Table 4;
5. Electrical equipment (Code V)—Table 5;
6. Other equipment under pressure (Code VI)—Table 6.

Table 1. Drilling equipment.

Code	Specific Part	Moving Parts?	Under Pressure?	Increased Temperature?	Leakage?
I1	Hoisting, lifting, handling, and rotary systems *	Yes	No	No	Yes
I2	Derrick structure and platform structure	Yes for movable derrick, otherwise No	No	No	No
I3	Tensioning and motion compensating systems	Yes	No	No	No
I4	Cementing system with cementing pumps, etc.	Yes	Yes	Yes	Yes
I5	String/pipes (drill string, casing, etc.)	No	Yes	No	Yes
I6	Marine riser	No	Yes	No	Yes
I7	Mud circulating system	Examined in more detail in Table 4; Well control equipment			

* including drawworks, crown block, travelling block, drilling hook, top drive/drilling machine, rotary table, pipe handling machines, BOP crane, X-mas tree crane, etc.

Table 2. Well intervention equipment.

Code	Specific Part	Moving Parts?	Under Pressure?	Increased Temperature?	Leakage?
II1	Wireline equipment	No	Yes	No	No
II2	Snubbing equipment	Yes	Yes	No	No
II3	Coiled tubing equipment	Yes	Yes	No	No

Table 3. Material handling equipment.

Code	Specific Part	Moving Parts?	Under Pressure?	Increased Temperature?	Leakage?
III1	Lifting appliances (cranes, etc.)	Yes	No	No	No
III2	Lifting gear (hooks, swivels, etc.) including towing equipment	Yes	No	No	No

Table 4. Well control equipment.

Code	Specific Part	Moving Parts?	Under Pressure?	Increased Temperature?	Leakage?
I7	Mud circulating system *	Yes	Yes	No	Yes
IV2	Blowout Preventers (BOPs) with their control units (BOP stacks, BOP control unit i.e., Koomey unit, etc.)	Yes	Yes	No	Yes
IV3	Well head (Christmas tree, choke manifold, etc.)	No	Yes	No	Yes
IV4	Packers	Yes	Yes	No	No
I4	Cementing system	Examined in more details in Table 1; Drilling equipment			
I5	String/pipes	Examined in more details in Table 1; Drilling equipment			

* including mud pumps, mixing units, mud centrifuge, mud cleaner, mud–gas separator, drilling pipes, bit, dampener, degasser, desilter, valves, conduits, etc.

These categories were first established and then the accidents were analyzed. The analysis focused not on general types of equipment but specifically on the role of specific equipment typically used in the oil and gas industry and its involvement in accidents.

Table 5. Electrical equipment *.

Code	Specific Part	Moving Parts?	Under Pressure?	Increased Temperature?	Leakage?
V1	Underwater systems and appliances (Remotely Operated Vehicles (ROVs))	Yes	No	No	No
V2	Electrical power systems (emergency power supply system—generator, emergency power distribution system, emergency battery, etc.)	No	No	Yes	No
V3	Uninterruptible power system	No	No	No	No
V4	Field equipment (public address flashing lights, junction boxes, etc.)	No	No	No	No
V5	Control systems (control and instrumentation, process control system, safety and automation system, etc.)	Yes	No	No	No
V6	Trace heating circuits	No	No	Yes	No

* In this case, sparking by electric discharge is possible [68].

Table 6. Other equipment under pressure *.

Code	Specific Part	Moving Parts?	Increased Temperature?	Leakage?
VI1	Separators and tanks	No	Yes	Yes
VI2	Emergency shut-down valves	Yes	No	Yes
VI3	Air hoist	Yes	No	No
VI4	Gas lift equipment	Yes	No	Yes
VI5	Pumps and compressors	Yes	Yes	Yes
VI6	Downhole motor (mud motor)	Yes	No	Yes
VI7	Hydraulic jar	Yes	No	No
VI8	Engines	Yes	Yes	Yes

* by definition always under pressure.

These categories were first established and then the accidents were analyzed. The analysis focused not on general types of equipment but specifically on the role of specific equipment typically used in the oil and gas industry and its involvement in accidents.

3.2. Offshore Accidents and Their Relations to Certain Types of Equipment

Large offshore oil and gas accidents are catastrophic events that can cause significant environmental damage, economic loss, and human casualties. Notable examples include the 2010 Deepwater Horizon disaster [69], which released millions of barrels of oil into the Gulf of Mexico, severely affecting marine life and coastal ecosystems. These accidents often result from equipment failure, human error, or safety oversight and highlight the inherent risks of deep-sea drilling. They have spurred stricter regulations and safety measures in the industry to prevent future occurrences. More about described accidents can be seen in [6].

The causes of accidents in mobile units according to Kaiser [70] are blowout (21%), design and workmanship events (13%), heavy weather and windstorm (15%), mechanical failure (7%), and anchor/jacking/trawl (5%). Additional causes can be material failure due to fatigue cracking [71–73], where the strength of the platform structure can be weakened due to fire [74,75], well cement quality [76–78] and cementing operations, offshore shallow gas blowouts [79], etc. Together with fire and explosions, the release of toxic substances in oil and gas disasters [80] are frequent; during the transportation of drilling fluids by platform supply-class vessel [81], accidents can occur. Systems under pressure, such as compressors, turbines, etc. [82], can be involved in these accidents.

The main accidents involving fire (Table 7) and those without fire (Table 8) are analyzed, with the largest accidents—those resulting in more than 10 fatalities—listed alongside significant accidents without casualties but with substantial environmental impact, which occurred between 1956 and 2010. The accidents are examined to determine if they can be matched with the equipment shown in Tables 1–6 and whether they occurred under a jurisdiction with prescriptive or goal-oriented legislation. In addition, the specific phase, such as drilling, production (exploitation), etc., is identified. Drilling facilities are typically mobile, while production facilities are fixed. Further information about the accidents in Tables 7 and 8 can be seen in Appendix A.

Table 7. Large offshore accidents with fire involved.

Accident	Fatalities	Cause	Type of Facility	Associated Equipment	Safety Regime	Country
Piper Alpha	167	Leak from pump	Production	Pumps and compressors VI5	Goal-oriented	UK
Bohai 3	70	Loss of stability and buoyancy due to bad weather	Drilling	Platform structure I2	Prescriptive	China
Enchova Central	42	Bad cementing	Production	Cementing system I4	Goal-oriented	Brazil
Mumbai High North	22	Hit by rescue vessel	Production	Emergency valves VI2	Prescriptive	India
Usumacinta	22	Collision due to bad weather	Drilling	Emergency valves VI2, Platform structure I2	Goal-oriented	Mexico
C.P. Baker	21	Shallow gas blowout	Drilling	Blowout Preventers (BOPs) IV2	Prescriptive	US
Petrobras P-36	11	Rupture in a tank,	Production	Separators and tanks VI1	Goal-oriented	Brazil
Nowruz platform	11	Collision with tanker during war	Production	-	Prescriptive	Iran
Macondo Deepwater Horizon	11	Bad cementing, BOP	Drilling	Cementing system I4, Blowout Preventers (BOPs) IV2	Prescriptive	US
Ixtoc I	0	Mud circulation stopped	Drilling	Mud circulating system I7	Goal-oriented	Mexico
Montara	0	Bad cementing	Production	Cementing system I4	Goal-oriented	Australia
Adriatic IV	0	Unknown	Drilling	-	Prescriptive	Egypt
Σ	377		6×Production; 6×Drilling		6×Prescriptive; 6×Goal-oriented	

The summaries in Tables 7 and 8 comparing the prescriptive and goal-oriented approaches do not account for the level of activity under the two regulatory regimes. They also fail to control for potential confounding factors, such as variations in the intrinsic hazards of different situations, e.g., one regime might be applied more frequently in scenarios with greater safety challenges.

Regarding fatalities and the type of offshore safety regime:

- Approximately 40% of the fatalities in the observed cases occurred in accidents involving fire;
- About 54% of the fatalities in the examined accidents occurred under prescriptive regimes, compared to 46% under goal-oriented regimes.

Regarding equipment use, material fatigue in offshore drilling facilities is the most common cause of accidents and such accidents are more likely to occur without fire, as shown in Table 9.

Table 8. Large offshore accidents without fire involved.

Accident	Fatalities	Cause	Phase	Associated Equipment	Safety Regime	Country
Alexander L. Kielland	123	Material fatigue	-	Platform structure I2	Goal-oriented	Norway
Seacrest	91	Bad weather, anchoring system failed	Drilling	Towing equipment III2	Prescriptive	Thailand
Ocean Ranger	84	Material fatigue, bad weather	Drilling	Platform structure I2	Hybrid	Canada
Glomar Java Sea	81	Bad weather	Drilling	Platform structure I2	Prescriptive	China
Bohai 2	72	Collapse during tow	Drilling	Platform structure I2; towing equipment III2	Prescriptive	China
DB 29	22	Collapse during tow	-	Platform structure I2; towing equipment III2	Prescriptive	China
Qatar 1 jack-up rig	20	Collapse during tow	Drilling	Platform structure I2; towing equipment III2	Prescriptive	Qatar
Hasbah 6	19	Blowout	Drilling	Blowout Preventers (BOPs) IV2	Prescriptive	Saudi Arabia
Sea Gem	19	Material failure	Drilling	Platform structure I2	Goal-oriented	UK
Gemini	18	Material failure	Drilling	Platform structure I2	Prescriptive	Egypt
Ocean Express	13	Lack of stability during tow	Drilling	Platform structure I2; towing equipment III2	Goal-oriented	Mexico
Ekofisk Bravo	0	Safety valve	Production	Electrical power systems VI2	Goal-oriented	Norway
Σ	562		1×Production; 9×Drilling		7.5×Prescriptive; 4.5×Goal-oriented	

Table 9. Equipment involved in different scenarios of accident with fire or without, type of facility, and type of safety regime *.

Total	Fire		Facility		Offshore Regime		Most Likely to Occur
	Yes	No	Drilling	Production	Prescriptive	Goal-Oriented	
Platform structure I2×11	I2×2	I2×9	I2×10	I2×0	I2×6.5	I2×4.5	No fire, drilling
Towing equipment III2×5	III2×0	III2×5	III2×4	III2×0	III2×4	III2×1	No fire, drilling
Cementing system I4×3	I4×3	I4×0	I4×1	I4×2	I4×1	I4×2	With fire
Blowout Preventers (BOPs) IV2×3	IV2×2	IV2×1	IV2×3	IV2×0	IV2×3	IV2×0	-
Emergency valves VI2×3	VI2×2	VI2×1	VI2×1	VI2×2	VI2×1	VI2×2	-
Mud circulating system I7×1	I7×1	I7×0	I7×1	I7×0	I7×0	I7×1	-
Separators and tanks VI1×1	VI1×1	VI1×0	VI1×0	VI1×1	VI1×0	VI1×1	-
Pumps and compressors VI5×1	VI5×1	VI5×0	VI5×0	VI5×1	VI5×0	VI5×1	-

* Table 9 is based on the findings from Tables 7 and 8.

4. Conclusions

Large offshore oil and gas accidents are rare events and there is insufficient evidence to determine whether they are more likely to occur with or without fire. Similarly, it remains inconclusive whether a specific safety regime—be it prescriptive or goal-oriented—is more effective in preventing such accidents [83,84].

The most frequent causes of offshore oil and gas accidents can be categorized as follows:

1. Structural Failures Without Fire: The most common type of accident typically occurs without fire and is primarily caused by material fatigue or corrosion [85,86]. These factors can lead to structural collapse, loss of buoyancy, and the capsizing of platforms, particularly under adverse weather conditions or during towing operations. Preventing such accidents often falls more under the purview of maritime regulations than those specifically tailored for the oil and gas industry. On an international level, the IMO MODU Code (A 26/Res. 1023) [87], which outlines construction and equipment standards for Mobile Offshore Drilling Units, plays a critical role in addressing such risks, especially for mobile vessels.
2. Well Control Failures and Fire Risks: Contrary to common belief, the most frequent accidents are not those involving fire triggered by the failure of a Blowout Preventer (BOP) following a well control issue. Instead, such accidents are the second most frequent and are often linked to cementing operations within the well. While BOP failures are critical and have been implicated in major accidents, their frequency is surpassed by structural and procedural issues related to well construction and maintenance.

Despite the rarity of large offshore accidents, fire hazards cannot be overlooked. Historical data indicate that approximately half of the largest offshore oil and gas accidents have ended in fire and/or explosions, underscoring the significant role fire plays in exacerbating the severity and consequences of these events.

To improve safety practices, a hybrid approach combining prescriptive and goal-oriented methods is recommended, leveraging clear regulations while allowing flexibility for innovation. Regularly updating prescriptive standards to reflect technological advances can enhance relevance. Encouraging a safety culture focused on continuous improvement and proactive risk management ensures adaptability to emerging challenges.

At first glance, it might be expected that a more prescriptive approach would result in fewer disputes over interpretation, which was actually not noticed in practice. Therefore, a goal-oriented approach should not be favored with that reasoning.

Funding: Financial support was received from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia through institutional financing, from the European Union under REFRESH—Research Excellence For REgion Sustainability and High-tech Industries, project number CZ.10.03.01/00/22_003/0000048, via the Operational Programme Just Transition, and by the Ministry of Education, Youth, and Sports of the Czech Republic through the e-INFRA CZ (ID:90254).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations and Notations

US	United States
EU	European Union
BOP	Blowout Preventers
MODUs	Mobile Offshore Drilling Units
OCSLA	Outer Continental Shelf Lands Act
DOI	Department of the Interior
MMS	Mineral Management Service
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BSEE	Bureau of Safety and Environmental Enforcement
BOEM	Bureau of Ocean Energy Management
ONRR	Office of Natural Resources Revenue
SEMS	Safety and Environmental Management Systems
NEPA	National Environmental Policy Act
OSHA	Occupational Safety and Health Administration
CFR	Code of Federal Regulations
API	American Petroleum Institute
RP	Recommended Practice
NTLs	Notices to Lessees
ALARP	As Low as Reasonably Practicable
PSA/PTIL	Petroleum Safety Authority
IOGP	International Association of Oil & Gas Producers
OPITO	Offshore Petroleum Industry Training Organization
BOSIET	Basic Offshore Safety Induction and Emergency Training
COS	left for Offshore Safety
IADC	International Association of Drilling Contractors
IMCA	International Marine Contractors Association
EUOAG	European Union Offshore Oil and Gas Authorities Group
NORSOK	a set of standards developed by the Norwegian petroleum industry
ROVs	Remotely Operated Vehicles
SWRP	Subsea Well Response Project
MWCC	Marine Well Containment Company
NOFO	Norwegian Clean Seas Association for Operating Companies
OIE	Offset Installation Equipment
IECeX	International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres
API RP 75	Recommended Practice for a Safety and Environmental Management System for Offshore Operations and Assets
API 16A	Specification for Drill-through Equipment
API 17D	Specification for Subsea Wellhead and Tree Equipment
NORSOK D-001	Drilling facilities
NORSOK D-010	Well integrity in drilling and well operations
2013/30/EU	Directive of the European Parliament and of the Council of 12 June 2013 on safety of offshore oil and gas operations
ATEX 2014/34/EU	Directive relating to equipment and protective systems intended for use in potentially explosive atmospheres
Pressure Equipment	2014/68/EU Directive relating to the making available on the market of pressure equipment
Machinery	2006/42/EC Directive on machinery
IMO MODU Code (A 26/Res. 1023)	Code for the construction and equipment of Mobile Offshore Drilling Units

Appendix A. Overview of Accidents from Tables 7 and 8

Accidents with fire:

1. The Piper Alpha disaster occurred in 1988, when an explosion and subsequent fires destroyed the offshore oil platform in the North Sea, killing 167 workers. The Piper Alpha disaster was caused by a gas leak resulting from the improper reinstatement of a pressure safety valve during maintenance. When the system was restarted, gas escaped from the open pipe, ignited, and triggered a catastrophic explosion and fire. It remains a pivotal event in the industry, leading to significant reforms in offshore oil and gas safety regulations worldwide.
2. The Bohai 3 accident occurred in 1980 in Chinese waters and the cause was a blowout.
3. The Enchova Central accident occurred in 1984 when a blowout on the offshore oil platform in Brazil's Campos Basin caused a massive fire, resulting in 42 fatalities.
4. The Mumbai High North accident occurred in 2005 in India when a multipurpose support vessel collided with the offshore platform, causing a fire that destroyed the structure and resulted in 22 fatalities. The collision was attributed to adverse weather conditions and operational errors during vessel maneuvering.
5. The Usumacinta accident occurred in 2007 when the jack-up rig collided with the platform in the Gulf of Mexico during a storm, causing gas leaks, explosions, and fires that killed 22 workers. The tragedy was linked to severe weather conditions, inadequate anchoring, and insufficient emergency preparedness.
6. The C.P. Baker accident occurred in 1964 when a shallow blowout on the offshore drilling rig in the Gulf of Mexico led to an explosion and fire, killing 21 crew members.
7. The Petrobras P-36 accident occurred in 2001 when explosions caused by a gas leak in the ballast tanks of the offshore platform led to its sinking off the coast of Brazil, killing 11 workers.
8. The Nowruz platform accident was caused by a collision with a tanker during the Iran–Iraq War in 1983. Risers were destroyed, resulting in an explosion and fire which led to significant damage and the loss of at least 11 lives (up to 70 or even more), all during Iraqi attack.
9. The Macondo Deepwater Horizon accident at the Macondo prospect occurred in 2010 when a blowout on a drilling rig in the Gulf of Mexico caused a massive explosion and fire, resulting in 11 worker fatalities. The blowout triggered one of the largest oil spills in history, releasing millions of barrels of oil into the ocean over several months. The disaster highlighted failures in well control, risk management, and safety practices, leading to major changes in offshore drilling regulations and industry practices.
10. The Ixtoc I accident occurred in 1979 on a Mexican offshore oil platform and was caused by a blowout.
11. The Montara accident occurred in 2009 when a blowout on the Montara offshore oil platform near the coast of Australia caused a massive oil spill. The accident resulted from a failure of well cement while the Blowout Preventer (BOP) was not installed at all.
12. The Adriatic IV accident occurred in 2004 near the Egyptian coast when a gas blowout during drilling caused a fire and explosion, damaging the platform beyond repair. The cause of the blowout remains unclear. Fortunately, production had been halted as a precaution and no fatalities occurred.

Accidents without fire:

1. The Alexander L. Kielland accident occurred in 1980 when a structural failure caused the Norwegian offshore floating hotel to collapse in the North Sea, killing 123 workers.

The disaster was attributed to a design flaw in the material of the platform's leg, which failed under wind but not under very heavy weather conditions.

2. The Seacrest drillship accident occurred in Thai waters in 1989, resulting in 91 fatalities. The disaster was primarily caused by poor storm prediction, inadequate weather warnings, stability issues with the ship, and a mechanical failure in the anchoring system, resulting in capsize of the platform.
3. The Ocean Ranger accident occurred in 1982 in Canada when the offshore oil rig capsized during a storm, killing all 84 crew members. The disaster was caused by a combination of severe weather, design flaws, and insufficient safety measures, particularly regarding the rig's stability in rough seas.
4. The Glomar Java Sea accident occurred in 1983 in Chinese waters and resulted in the tragic loss of 81 lives. The accident was caused by a combination of harsh weather conditions and structural issues on the offshore drilling rig, leading to its capsizing.
5. The Bohai 2 accident, which occurred in 1979 in China, resulted in the loss of 72 lives. The cause was the inappropriate stowing of deck equipment during a storm.
6. The DB-29 accident occurred in 1991 in the South China Sea when the pipe-laying vessel capsized during towing operations, resulting in 22 fatalities. The disaster was attributed to stability issues and operational risks in challenging conditions.
7. The Qatar 1 jack-up rig accident occurred in December 1956 during towing operations in the Persian Gulf. The rig capsized, resulting in the deaths of 20 workers.
8. The Hasbah 6 accident occurred in 1980 in the Arabian Gulf when a blowout during drilling operations resulted in 19 fatalities. The disaster was caused by a subsequent failure of a Blowout Preventer (BOP).
9. The Sea Gem accident occurred in 1965 when the offshore drilling rig capsized in the North Sea, killing 19 workers while equipment and people slid off. The disaster was mainly caused by corrosion, temperature changes, and cyclic loading on the legs.
10. The Gemini jack-up rig accident, with 18 fatalities, occurred in the Gulf of Suez in 1974 and the cause was leg failure.
11. The Montara platform accident occurred in Australian waters in 2009, with no fatalities, following a blowout caused by well cement failure, leading to a major oil spill.
12. The Ekofisk Bravo production platform blowout occurred in Norwegian waters in 1977, with no fatalities. The accident was caused by human error during maintenance operations, specifically the incorrect installation of a downhole safety valve. It happened during a workover on the production well when the production tubing was being pulled and the Blowout Preventer (BOP) had not yet been installed.

More about on both types of accidents, with and without fire occurrence, can be seen in [6].

References

1. Day, J.W.; Rivera-Arriaga, E.; del Carmen Peña-Puch, A.; Hunter, R.G. Sustainability of Gulf of Mexico coastal estuaries and lagoons: Interactions with hydrocarbon production—A review with a look to the future. *Sustainability* **2024**, *16*, 8601. [CrossRef]
2. Sharp, S.M.; Gomez, F.M.; Meegan, J.M.; Rowles, T.K.; Townsend, F.; Schwacke, L.H.; Smith, C.R. Using blood gas analysis and capnography to determine oxygenation status in bottlenose dolphins (Tursiops Truncatus) following the Deepwater Horizon oil spill. *Toxics* **2023**, *11*, 423. [CrossRef]
3. Edwin, K.W.; Nilsen, M.; Albrechtsen, E. Why is the construction industry killing more workers than the offshore petroleum industry in occupational accidents? *Sustainability* **2021**, *13*, 7592. [CrossRef]
4. D'Antoine, E.; Jansz, J.; Barifcani, A.; Shaw-Mills, S.; Harris, M.; Lagat, C. Psychosocial safety and health hazards and their impacts on offshore oil and gas workers. *Safety* **2023**, *9*, 56. [CrossRef]
5. Brkić, D.; Stajić, Z. Offshore oil and gas safety: Protection against explosions. *J. Mar. Sci. Eng.* **2021**, *9*, 331. [CrossRef]

6. Brkić, D.; Praks, P. Probability analysis and prevention of offshore oil and gas accidents: Fire as a cause and a consequence. *Fire* **2021**, *4*, 71. [CrossRef]
7. Ray, A.; Rajashekara, K. Electrification of offshore oil and gas production: Architectures and power conversion. *Energies* **2023**, *16*, 5812. [CrossRef]
8. Wang, H.; Liu, Z.; Wang, X.; Graham, T.; Wang, J. An analysis of factors affecting the severity of marine accidents. *Reliab. Eng. Syst. Saf.* **2021**, *210*, 107513. [CrossRef]
9. Zhang, D.; Zhou, T.; Liu, Z.; Yang, H.; Bie, R.; Zhang, M. Matching Analysis of technical parameters and safety standards for nuclear replacement of coal-fired units. *Energies* **2024**, *17*, 5583. [CrossRef]
10. Koutsoudaki, M.; Bain, B.; Duijm, N.J.; Kozine, I. Trends in causes of offshore releases by severity classification. *J. Loss Prev. Process Ind.* **2020**, *68*, 104283. [CrossRef]
11. Amaechi, C.V.; Reda, A.; Kgosiemang, I.M.; Ja'e, I.A.; Oyetunji, A.K.; Olukolajo, M.A.; Igwe, I.B. Guidelines on asset management of offshore facilities for monitoring, sustainable maintenance, and safety practices. *Sensors* **2022**, *22*, 7270. [CrossRef] [PubMed]
12. Jain, P.; Reese, A.M.; Chaudhari, D.; Mentzer, R.A.; Mannan, M.S. Regulatory approaches-safety case vs us approach: Is there a best solution today? *J. Loss Prev. Process Ind.* **2017**, *46*, 154–162. [CrossRef]
13. Barua, S.; Gao, X.; Mannan, M.S. Comparison of prescriptive and performance-based regulatory regimes in the USA and the UK. *J. Loss Prev. Process Ind.* **2016**, *44*, 764–769. [CrossRef]
14. Norina, N. Types of offshore drilling platforms. In Proceedings of the E3S Web of Conferences: International Scientific Siberian Transport Forum—TransSiberia 2024, EDP Sciences, Novosibirsk, Russian, 27–30 May 2024; Tanaino, I., Popović, Z., Eds.; Volume 549, p. 07004. [CrossRef]
15. Cherepovitsyn, A.; Lebedev, A. Drill cuttings disposal efficiency in offshore oil drilling. *J. Mar. Sci. Eng.* **2023**, *11*, 317. [CrossRef]
16. Baram, M. The U.S. Regulatory regime for preventing major accidents in offshore operations. In *Risk Governance of Offshore Oil and Gas Operations*; Lindøe, P.H., Baram, M., Renn, O., Eds.; Cambridge University Press: Cambridge, UK, 2013; pp. 154–187. [CrossRef]
17. Mrozowska, A. Review of the provisions of the European Parliament and of the Council Directive 2013/30/UE on safety of offshore oil and gas operations. *Polityka Energetyczna-Energy Policy J.* **2018**, *21*, 103–124. [CrossRef]
18. Mrozowska, A. Formal risk assessment of the risk of major accidents affecting natural environment and human life, occurring as a result of offshore drilling and production operations based on the provisions of Directive 2013/30/EU. *Saf. Sci.* **2021**, *134*, 105007. [CrossRef]
19. Morais, C.H.; Abreu, D.T.; Santos, J.; Maturana, M.C.; Colombo, D.; Martins, M.R. The Influence of non-prescriptive legislation in the evolution of offshore well integrity practices: An exploratory review. In Proceedings of the 38th International Conference on Ocean, Offshore and Arctic Engineering, Glasgow, Scotland, UK, 9–14 June 2019; American Society of Mechanical Engineers: New York, NY, USA; Volume 58783, p. V003T02A082. [CrossRef]
20. Brkić, D.; Praks, P. Proper use of technical standards in offshore petroleum industry. *J. Mar. Sci. Eng.* **2020**, *8*, 555. [CrossRef]
21. Knol-Kauffman, M.; Solås, A.M.; Arbo, P. Government-industry dynamics in the development of offshore waste management in Norway: From prescriptive to risk-based regulation. *J. Environ. Plan. Manag.* **2021**, *64*, 649–670. [CrossRef]
22. Acheampong, T.; Phimister, E.; Kemp, A. What difference has the Cullen Report made? Empirical analysis of offshore safety regulations in the United Kingdom′s oil and gas industry. *Energy Policy* **2021**, *155*, 112354. [CrossRef]
23. Jespen, T. ATEX—Equipment selection. In *ATEX—Explosive Atmospheres*; Springer Series in Reliability Engineering; Springer: Cham, Switzerland, 2016. [CrossRef]
24. Keane, B.; DeSousa, T.; Simpson, W.; McVeigh, J. Equipment assemblies for explosive atmospheres. *IEEE Trans. Ind. Appl.* **2022**, *58*, 5667–5674. [CrossRef]
25. Xie, X.; Xiong, Y.; Xie, W.; Li, J.; Zhang, W. Quantitative risk analysis of oil and gas fires and explosions for FPSO systems in China. *Processes* **2022**, *10*, 902. [CrossRef]
26. Amaechi, C.V.; Reda, A.; Butler, H.O.; Ja'e, I.A.; An, C. Review on fixed and floating offshore structures. Part I: Types of platforms with some applications. *J. Mar. Sci. Eng.* **2022**, *10*, 1074. [CrossRef]
27. Pitblado, R.; Bjerager, P. Offshore major accident safety: Is SEMS enough? In Proceedings of the Offshore Technology Conference, Offshore Technology Conference, Houston, TX, USA, 6–9 May 2013; p. OTC-23922. [CrossRef]
28. McKelvey, V.E. Environmental protection in offshore petroleum operations. *Ocean Manag.* **1973**, *1*, 119–127. [CrossRef]
29. Laskar, S.; Mallinson, T.; Aldeeb, A. Offshore safety through design: Practical implementation of best practices from the OSHA 1910 framework. In Proceedings of the SPE Health Safety, Security, Environment, & Social Responsibility Conference-North America, Houston, TX, USA, 21–23 March 2011; p. SPE-141938. [CrossRef]
30. Sutton, I. Analysis of the SEMS II safety management rule. In Proceedings of the SPE Health, Safety, Security, Environment, & Social Responsibility Conference-North America, Galveston, TX, USA, 18–20 March 2013; p. SPE-163806. [CrossRef]

31. Gordillo, G.; Lopez-Videla, L. Managing SEMS audits: Past, present, and future. *J. Pet. Technol.* **2014**, *66*, 72–75. [CrossRef]
32. Steinzor, R. Lessons from the North Sea: Should Safety Cases Come to America. *Boston Coll. Environ. Aff. Law Rev.* **2011**, *38*, 417–444. Available online: https://lira.bc.edu/work/sc/e9decb95-f03b-428a-bd62-45ec126cf531 (accessed on 15 October 2024).
33. Arnold, K.E.; Breskr, R.A.; Sikes, C.T. An engineering contractor's perspective on API RP 75 and RP 14J. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 1–4 May 1995; p. OTC-7735. [CrossRef]
34. Watkins, P.D.; Roueche, J.N.; Miller, D.L. American Petroleum Institute standards and other initiatives in support of the energy transition. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2024; p. D031S038R002. [CrossRef]
35. Velez, P.K.; Liles, C.O.; Satterlee, K. An overview of API RP 75 and RP 14J. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 1–4 May 1995; p. OTC-7732. [CrossRef]
36. Averill, L.; Durkin, B.; Chu, M.; Ougradar, U.; Reeves, A. Deepwater Horizon Disaster. *Loss Prev. Bull.* **2022**, *285*, 7–12. Available online: https://www.icheme.org/media/18486/lpb285_pg07.pdf (accessed on 15 October 2024).
37. Sheppard, J.P.; Young, J. An essential stupidity-based review of the Deepwater Horizon disaster. *Bus. Horiz.* **2023**, *66*, 65–73. [CrossRef]
38. Kujawinski, E.B.; Reddy, C.M.; Rodgers, R.P.; Thrash, J.C.; Valentine, D.L.; White, H.K. The first decade of scientific insights from the Deepwater Horizon oil release. *Nat. Rev. Earth Environ.* **2020**, *1*, 237–250. [CrossRef]
39. Ulmer, R.R.; Pyle, A.S. Finding renewal in the midst of disaster: The case of the deepwater horizon oil spill. *Public Relat. Rev.* **2021**, *47*, 102001. [CrossRef]
40. Antonsen, S.; Nilsen, M.; Almklov, P.G. Regulating the intangible. Searching for safety culture in the Norwegian petroleum industry. *Saf. Sci.* **2017**, *92*, 232–240. [CrossRef]
41. Ibrion, M.; Paltrinieri, N.; Nejad, A.R. Learning from failures: Accidents of marine structures on Norwegian continental shelf over 40 years time period. *Eng. Fail. Anal.* **2020**, *111*, 104487. [CrossRef]
42. Nilsen, M.; Størkersen, K.V. Permitted to be powerful? A comparison of the possibilities to regulate safety in the Norwegian petroleum and maritime industries. *Mar. Policy* **2018**, *92*, 30–39. [CrossRef]
43. de Almeida, A.G.; Vinnem, J.E. Major accident prevention illustrated by hydrocarbon leak case studies: A comparison between Brazilian and Norwegian offshore functional petroleum safety regulatory approaches. *Saf. Sci.* **2020**, *121*, 652–665. [CrossRef]
44. Reid, M. The Piper Alpha disaster: A personal perspective with transferrable lessons on the long-term moral impact of safety failures. *ACS Chem. Health Saf.* **2020**, *27*, 88–95. [CrossRef]
45. Špelić, I.; Mihelić-Bogdanić, A. EU environmental protection in regard to sustainable development: Myth or reality? *Standards* **2024**, *4*, 176–195. [CrossRef]
46. Engen, O.A.; Lindøe, P.H.; Braut, G.S. Coping with different system logics of standardization in regulatory regimes. Norwegian offshore experience. *Saf. Sci.* **2023**, *161*, 106079. [CrossRef]
47. Yakushev, V. Environmental and technological problems for natural gas production in permafrost regions. *Energies* **2023**, *16*, 4522. [CrossRef]
48. Wang, S.; Zhang, L.; Yu, J.; Fan, J. Influence of top seal damage on contact seal in ram Blowout Preventer. *Materials* **2023**, *16*, 3413. [CrossRef] [PubMed]
49. Shafiee, M.; Enjema, E.; Kolios, A. An integrated FTA-FMEA model for risk analysis of engineering systems: A case study of subsea Blowout Preventers. *Appl. Sci.* **2019**, *9*, 1192. [CrossRef]
50. Shafiee, M.; Elusakin, T.; Enjema, E. Subsea blowout preventer (BOP): Design, reliability, testing, deployment, and operation and maintenance challenges. *J. Loss Prev. Process Ind.* **2020**, *66*, 104170. [CrossRef]
51. Rassenfoss, S. Macondo changed BOPs but there is a limit. *J. Pet. Technol.* **2020**, *72*, 17–21. [CrossRef]
52. *NORSOK D-001*; Drilling Facilities. Standard Norge: Oslo, Norway, 2023.
53. *NORSOK D-010*; Well Integrity in Drilling and Well Operations. Standard Norge: Oslo, Norway, 2021.
54. Choueri Jr, N.; Jaculli, M.A.; Leite, A.G.A.S.; Mendes, J.R.P. Use of graphs to assess well safety in drilling projects and during operations by identification of available barrier elements and consolidation of barrier envelopes. *Pet. Res.* **2024**, *9*, 418–431. [CrossRef]
55. Khalifeh, M.; Saasen, A. General Principles of Well Barriers. In *Introduction to Permanent Plug and Abandonment of Wells*; Ocean Engineering & Oceanography; Springer: Cham, Switzerland, 2020; Volume 12. [CrossRef]
56. Fjagesund, T. Technology update: Using schematics for managing well barriers. *J. Pet. Technol.* **2015**, *67*, 34–37. [CrossRef]
57. Jaculli, M.A.; Choueri Jr, N.; da Mata, C.R.; Leite, A.G.A.S.; Mendes, J.R.P.; Colombo, D. Well safety and integrity evaluation of offshore wells: A review of past, present, and future. *J. Pet. Sci. Eng.* **2022**, *212*, 110329. [CrossRef]
58. Satiarvand, M.; Orak, N.; Varshosaz, K.; Hassan, E.M.; Cheraghi, M. Providing a comprehensive approach to oil well blowout risk assessment. *PLoS ONE* **2023**, *18*, e0296086. [CrossRef]

59. Zhu, J.; Chen, G.; Zhang, S. Emergency risk analysis of subsea capping stack in blowout scenario integrating numerical simulation with ANN model. *Ocean Eng.* **2024**, *296*, 116727. [CrossRef]
60. Pessanha Santos, N.; Moura, R.; Lourenço Antunes, T.; Lobo, V. Revolutionizing ocean cleanup: A Portuguese case study with unmanned vehicles fighting spills. *Environments* **2024**, *11*, 224. [CrossRef]
61. Vasconcelos, R.N.; Lima, A.T.C.; Lentini, C.A.D.; Miranda, J.G.V.; de Mendonça, L.F.F.; Lopes, J.M.; Santana, M.M.M.; Cambuí, E.C.B.; Souza, D.T.M.; Costa, D.P.; et al. Deep learning-based approaches for oil spill detection: A bibliometric review of research trends and challenges. *J. Mar. Sci. Eng.* **2023**, *11*, 1406. [CrossRef]
62. Haas, R.E. Problems with certification and legislation. *Mar. Struct.* **1989**, *2*, 181–191. [CrossRef]
63. Marucci, T.F.; McDaniel, D.E. Safety of Mobile Offshore Drilling Units. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 21–23 April 1970; p. OTC-1321. [CrossRef]
64. Vinnem, J.E. Risk due to miscellaneous hazards. In *Offshore Risk Assessment*; Springer: Dordrecht, The Netherlands, 1999. [CrossRef]
65. Waqar, A.; Othman, I.; Shafiq, N.; Mansoor, M.S. Evaluating the critical safety factors causing accidents in downstream oil and gas construction projects in Malaysia. *Ain Shams Eng. J.* **2024**, *15*, 102300. [CrossRef]
66. Ferreira, N.N.; Martins, M.R.; Dziedzic, R.; de Figueiredo, M.A.G. Obsolescence management for offshore oil and gas production facility life extension. *Ocean Eng.* **2023**, *285*, 115388. [CrossRef]
67. Ghaithan, A.; AlShamrani, O.; Mohammed, A.; Alshibani, A. Proactive framework for obsolescence management of electrical equipment in oil and gas industry. *J. Qual. Maint. Eng.* **2024**, *30*, 493–507. [CrossRef]
68. Pan, C.; Yin, L.; Chen, H.; Fu, H.; Li, T.; Wang, X. Investigation on vented ethanol-gasoline vapor explosion characteristics initiated via single and dual sparks. *Case Stud. Therm. Eng.* **2024**, *63*, 105339. [CrossRef]
69. Joye, S.B. Deepwater Horizon, 5 years on. *Science* **2015**, *349*, 592–593. [CrossRef] [PubMed]
70. Kaiser, M.J. World offshore energy loss statistics. *Energy Policy* **2007**, *35*, 3496–3525. [CrossRef]
71. Almar-Naess, A.; Haagensen, P.J.; Lian, B.; Moan, T.; Simonsen, T. Investigation of the Alexander L. Kielland failure—Metallurgical and fracture analysis. *J. Energy Resour. Technol. Mar.* **1984**, *106*, 24–31. [CrossRef]
72. Fang, X.; Wang, H.; Li, W.; Liu, G.; Cai, B. Fatigue crack growth prediction method for offshore platform based on digital twin. *Ocean Eng.* **2022**, *244*, 110320. [CrossRef]
73. Hajinezhadian, M.; Behnam, B. A Corrosion- and repair-based reliability framework for offshore platforms. *J. Mar. Sci. Eng.* **2024**, *12*, 504. [CrossRef]
74. Li, D. Mechanical Reliability and fire resistance limits of load-bearing columns on offshore platform frames. *Ocean Eng.* **2024**, *297*, 117082. [CrossRef]
75. Gravit, M.; Dmitriev, I.; Shcheglov, N.; Radaev, A. Oil and gas structures: Forecasting the fire resistance of steel structures with fire protection under hydrocarbon fire conditions. *Fire* **2024**, *7*, 173. [CrossRef]
76. Hussain, A.; Emadi, H.; Thiyagarajan, S.R.; Fernandez, D.M.; Ispas, I.; Watson, M. Non-destructive cyclic analysis of sealing ability of well cement for seasonal underground hydrogen storage. *Appl. Sci.* **2024**, *14*, 7973. [CrossRef]
77. Zhang, Z.; Yuan, Z.; Ye, S.; Li, Y.; Yang, L.; Pang, X.; Lv, K.; Sun, J. The influence of cyclic loading on the mechanical properties of well cement. *Energies* **2024**, *17*, 3856. [CrossRef]
78. Li, C.; Jin, Y.; Guan, Z.; Dang, Z.; Jin, J.; Zhang, B. New quantitative risk prediction method of deepwater blowout: Case study of Macondo well accident. *Energy Sources Part A Recovery Util. Environ. Eff.* **2021**, 1–20. [CrossRef]
79. Yin, Z.; Ma, Y.; Yang, X.; Yan, X.; Han, Z.; Liang, Y.; Zhang, P. Study on numerical simulation of formation deformation laws induced by offshore shallow gas blowout. *Processes* **2024**, *12*, 378. [CrossRef]
80. Alrbaihat, M.R. Release of toxic substances in disasters of oil, gas, and petrochemical units. In *Crises in Oil, Gas and Petrochemical Industries*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 201–215. [CrossRef]
81. Sagin, S.V.; Karianskyi, S.; Sagin, S.S.; Volkov, O.; Zablotskyi, Y.; Fomin, O.; Píštěk, V.; Kučera, P. Ensuring the safety of maritime transportation of drilling fluids by platform supply-class vessel. *Appl. Ocean Res.* **2023**, *140*, 103745. [CrossRef]
82. Amini, A.; Vakylabad, A.B.; Rahimpour, M.R. Pressurizing and work generation systems safety: Compressors, turbines, etc. In *Crises in Oil, Gas and Petrochemical Industries*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 125–158. [CrossRef]
83. Di Nardo, M.; Gallo, M.; Murino, T.; Santillo, L.C. System dynamics simulation for fire and explosion risk analysis in home environment. *Int. Rev. Model. Simul.* **2017**, *10*, 43–54. [CrossRef]
84. Di Nardo, M.; Madonna, M.; Santillo, L.C. Safety management system: A system dynamics approach to manage risks in a process plant. *Int. Rev. Model. Simul.* **2016**, *9*, 256–264. [CrossRef]
85. Imran, M.H.; Khan, M.I.; Jamaludin, S.; Hasan, I.; Ahmad, M.F.B.; Ayob, A.F.M.; bin Wan Nik, W.M.N.; Suhrab, M.I.R.; Zulkifli, M.F.R.B.; Afrizal, N.B.; et al. A critical analysis of machine learning in ship, offshore, and oil & gas corrosion research, part I: Corrosion detection and classification. *Ocean Eng.* **2024**, *313*, 119600. [CrossRef]

86. Imran, M.M.H.; Jamaludin, S.; Ayob, A.F.M.; Ali, A.A.I.M.; Ahmad, S.Z.A.S.; Akhbar, M.F.A.; Suhrab, M.I.R.; Zainal, N.; Norzeli, S.M.; Mohamed, S.B. Application of artificial intelligence in marine corrosion prediction and detection. *J. Mar. Sci. Eng.* **2023**, *11*, 256. [CrossRef]
87. Mitropoulos, E.E. Safety Offshore-The Work Of IMO. *WIT Trans. Built Environ.* **1993**, *1*, 12. Available online: https://www.witpress.com/elibrary/wit-transactions-on-the-built-environment/1/13356 (accessed on 15 November 2024).