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Original Paper

Safety design principles and best engineering practices for well stimulation vessels

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Abstract: Many offshore supply vessels are actively involved in well stimulation and well intervention operations in the Gulf of Mexico and other parts of the world. The potential risks associated with these operations are significantly high when the operation profile includes the exposure of hydrocarbon returns, carriage of low-flash point liquids, and handling and transport of liquefied nitrogen and other hazardous chemicals. Identification of the hazards, operational limitations, and risks that may be faced during these operations is important for preventing accidents which can damage property, the environment and endanger lives. Many of these vessels are not purpose-built but are mobilized for temporary assignments, i.e., specific stimulation and intervention jobs. This type of vessel is chartered with a very short notice within a short time frame. Preparing the vessel to safely perform the required tasks within the framework of the required rules and regulations is challenging for designers, operators, shipyards, and classification societies. Because each operation and vessel is unique, no universal rules or guidelines currently exist to cover the wide range of operational profiles. In this study, various existing rules, references, standards, and guidelines that are relevant to well stimulation operations were reviewed. Various operational risks of different well stimulation operations, safety arrangements, design considerations, and best engineering practices were discussed and recommended in order to satisfy the relevant safety objectives and functional requirements. The proposed key design recommendations may be considered at the early design stage of newbuilding or temporary mobilization projects to enhance the overall safety and prevent undesirable incidents in well stimulation vessels.

Keywords: Safety design, Well stimulation, Offshore supply vessel, Risk, Hydrocarbon

1. Introduction

The aging installed base of subsea wells is forecasted to surpass 7,000 by 2019, and operators are exhibiting a growing interest in improving the recovery rates of existing and future subsea wells **[1]**. Well stimulation is a well intervention method performed on an oil or gas well to increase production by improving the flow of hydrocarbons from the drainage area into the well bore **[2]**. It is a type of light well intervention that involves high-pressure pumping of fluids into the wells to break or fracture reservoirs. The potential risks associated with temporary mobilization for well operations in offshore supply vessels (OSVs) are significantly high due to the nature of handling hydrocarbons, chemicals, and hazardous liquids or gases during the operations. Some publications indicate the recent statistics of offshore incidents, which include loss of well controls **[3][4]**.

Safe, effective, and cost-efficient well stimulation and well intervention operations are beneficial for all stakeholders, including regulators, vessel owners, and oil and gas producers. Owing to the unique nature of each temporary mobilization job, there are no universal rules or guidelines addressing the wide range of well stimulation operations and the various chemical additives and equipment used in these activities.

In this study, various safety aspects of the design and operations in typical well stimulation vessels were investigated that utilize chemical injection and hydraulic fracturing as the main methods of well stimulation, with consideration of the possible fire and explosion risks, environmental pollution, and personal safety during operations. Various key parameters which are to be considered in the design, construction, and operational procedures were addressed to limit accidental events and enhance the overall safety of well stimulation vessels. Proper and inherent

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safety barriers implemented within the design and operational procedures are essential for enhancing the overall safety and reducing risks. The topics considered include the general arrangement and layout, fire protection and detection, ventilation, hazardous-area control, emergency shutdown (ESD) and disconnection system, emergency response and personal protection. The findings and recommendations presented herein are intended to enhance the overall safety level regarding designs and safety procedures. The major recommendations highlighted in the paper may be considered (to the extent that they are practical) for existing well stimulation vessels, temporary mobilization, and newbuilding projects.

2. Rules, Standards and Guidelines

There are numerous international codes, standards, rules, and guidelines that can be referred and implemented in well stimulation safety design, arrangement and procedures. Each classification society has its own rule sets to guide and specify requirements for different projects and vessels. The objectives of the rules and guidelines are to provide an internationally acceptable standard of safety by defining the requirements for the design loads, arrangements, area classification, shutdown logic, alarms, escape ways, and communication; to provide a contractual reference document between suppliers and purchasers; to provide guidelines for designers, suppliers, purchasers, and regulators; and to specify procedures and requirements for units and installations **[5]**.

This section addresses various requirements from existing codes, standards, rules, and guidelines. Additionally, comparisons and gap analyses between relevant rules and guidelines are performed. These references were collected, reviewed, and summarized to identify the essential requirements to be considered in the design and operations of well stimulation vessels.

IMO A.673(16) was developed for the design, construction, and operation of offshore support vessels that transport limited amounts of hazardous and noxious liquid substances in bulk for servicing and resupplying offshore platforms, mobile offshore drilling units, and other offshore installations, including those employed in the search for and recovery of hydrocarbons from the seabed **[6]**. The guideline is used for various offshore activities related to well stimulation and well intervention. Generally, this guideline together with the International Bulk Code (IBC) **[7]** and SOLAS **[8]** are baseline requirements of most of flag states and classification societies. The guidelines cover damage stabilities, various ship designs and arrangements, various safety aspects, pollution prevention, personal protection, and operational requirements. The IBC **[7]** contains the IMO regulations that govern the design, construction, and safety requirements for various chemicals and liquids used for well stimulation operations.

The FSS Code **[9]**, FTP Code **[10]** and SOLAS Ch. II-2 describe the mandatory requirements for active and passive firefighting systems, detection, personnel protection, and safe escape. The LSA Code **[11]** and SOLAS Chapter III describe lifesaving appliances and arrangements as a part of the safety barrier. USCG has a CG-ENG Policy Letter No.03-12 **[12]** regarding the implementation of IMO Resolutions A.673(16) and provides the United States' interpretations for the design, construction, and operation of new and existing U.S. flagged OSVs.

The DNV GL **[13]** and ABS **[14]** rules specifically address the safety design requirements for tank systems and equipment, piping systems, and control and monitoring systems, personnel protective equipment, intact and damage stability applicable to well stimulation vessels. The principle of safety design for both the rules are the same, but each classification society has slightly different rule details and descriptions.

MARPOL **[15]** regulates the control of pollution by noxious liquid substances in bulk in Annex II and the prevention of pollution by harmful substances in Annex III, which are used as chemicals and additives during well stimulation activities.

API RP 505 **[16]** and IEC 60092 **[17]** specify the hazardous area classification and selection of electrical equipment in vessels carrying liquids that are flammable—either inherently or because of their reaction with other substances—or flammable liquefied gases. Area classification is a method for analyzing and classifying the areas that may contain explosive gas atmospheres. The objective of the area classification is to limit the potential ignition sources and allow the selection of electrical apparatus that can be operated safely in these areas.

IMO Circ. 1321 **[18]** specifies the control of flammable material and ignition sources, the lighting within the cargo pump room space, the temperature monitoring system and gas detection system for cargo pumps, and the ventilation control in the cargo pump room space. Cargo pump rooms should be mechanically ventilated, and the capacity of the fan should be at least 20 air changes per hour of the total volume of the cargo pump room as per this circular.

IMO MSC/Circ. 1165 **[19]** provides principal requirements for the water-based fire-extinguishing system used in the cargo pump room.

IMO Circ. 672 **[20]** addresses measures for preventing explosions in the cargo pump room, including pump shaft temperature-sensing devices, alarms, lighting interlock with ventilation, a gas detection system in the pump room, and a bilge level monitoring system in the pump room.

The MODU Code **[21]** covers all the safety barriers, such as prevention and detection mitigation and emergency response, which includes machinery and electrical installation fire safety and lifesaving equipment and procedures.

The OCIMF “An Information Paper on P/R Safety” **[22]** specifies recommendations for various design aspects for pump room safety. These aspects include monitoring, detection, entry procedures, inspection and maintenance.

NORSOK S-001 **[23]** specifies a risk reduction principle. The objectives of the risk reduction principle and the inherent safety design are to reduce potential hazards, reduce the probability of unwanted events, reduce the inventory and damage potential, strive for simplicity and reliability, and prevent escalation. The layout, safety design, detection, ignition source control, communication, passive and active fire-fighting system, escape and evacuation, etc. are addressed.

An inherently safe design for well stimulation operations should use a combination of rules, standards, guidelines, and industrial best engineering practices to address all the safety barriers for avoiding undesirable incidents. The mandatory regulatory requirements (such as SOLAS and the rules of classification societies) pertain to only the baseline mandatory requirements, which should be strengthened according to the technical and safety standards, procedures and best engineering practices of the operators and designers.

3. Design Considerations to Enhance Safety

In this section, various design features and design requirements are reviewed, with a focus on the main safety barriers that must be considered in the design and operations of a vessel, such as prevention, detection and control, mitigation and egress, and emergency response. The following key design considerations for ensuring the safe operations of well stimulation vessels are discussed.

- General arrangement and layout
- Active and passive fire protection system
- Fire and gas detection system
- Electrical installation and hazardous area control
- Pump room ventilation and cargo tank vent system
- Process and piping system, as well as other safety design
- Emergency shut down (ESD) system
- Acid and cryogenic spill protection and safety design
- Chemicals and additives
- Emergency response and personal protection
- Operation manuals and procedures

The design features and recommendations presented in this section are high-level and key items that are addressed in the SOLAS **[8]**, IMO A.673(16) **[6]**, and Classification Society’s rules **[13][14]**. Various rules and guidelines are employed to make useful recommendations for enhancing the safety of the well stimulation vessel design. Additionally, the experience of the author from many temporary well stimulation mobilization projects and newbuilding projects is used to identify key issues in design and installation.

3.1 General arrangement and layout

Well stimulation vessels are equipped with various additional equipment and items compared with general offshore supply or support vessels, such as acid tanks, well stimulation equipment and tools, fuel tanks, control cabins, hydraulic power units (HPUs), generators, cryogenic tanks and piping, additive chemicals, mixers and blenders and associated piping for uninhibited acid, chemical pumps and high-pressure injection pumps, filters, dry chemical storage spaces, hose reels, injection manifolds, and liquid additive skids. Well stimulation vessels are also equipped with a dynamic positioning system in order to maintain their position safely during well stimulation operations. The arrangement of the system and equipment must consider various safety barriers, such as prevention, detection and control, mitigation and egress, and emergency response. The important design principle of “General Arrangement and Layout” is to ensure segregation and separation between high-risk hazardous spaces and low-risk nonhazardous spaces, as well as spaces containing important safety and control functions, machinery spaces, and accommodation and service spaces. In offshore units, the arrangement and layout undergo a formal safety assessment (e.g., hazard identification: HAZID hazard and operability study: HAZOP) to identify various potential hazards and risks. This additional assessment is not mandatory for SOLAS vessels, but it is recommended that equivalent risk assessments should be considered during the design phase.

Figure 1 : Aft deck arrangement of the well stimulation vessel

Figure 1 shows the one of the aft deck arrangement of the well stimulation vessel that is equipped with various well stimulation equipment, chemical and addictive tanks, a control cabin, a fixed foam firefighting system, etc. The arrangement indicates the complexity of the well stimulation area due to the size restriction of OSVs. Well stimulation equipment should be properly secured and attached to the hull structure of the vessel using a suitable means of fastening as per the approved cargo securing manual for the vessel, and the securing arrangements should not adversely affect the equipment operation, emergency response, or escape of personnel **[14]**.

IMO A.673(16) **[6]**, DNV GL **[13]**, and ABS **[14]** have the following common arrangement requirements for well stimulation vessels.

- Tanks for acid(s) and liquefied nitrogen are to be located at least 760 mm (30 inches) from the side shell of the vessel—measured perpendicularly inboard from the side of the vessel to the centerline at the level of the summer loadline—and at least 760 mm (30 inches) from the bottom.
- The tanks and pumping arrangements for the well stimulation processing plants are to be segregated from machinery spaces, propeller shaft tunnels (if present), dry cargo spaces, accommodation and service spaces, drinking water and stores for human consumption (via a cofferdam), void spaces, the cargo pump room, empty tanks, oil fuel tanks, and similar arrangement. The on-deck stowage of independent tanks or the installation of independent tanks in otherwise empty hold spaces should be considered for satisfying this requirement.
- Cargoes that react with other cargoes or oil fuels in a hazardous manner should be segregated from such other cargoes or oil fuels using a cofferdam, a void space, a cargo pump room, a pump room, an empty tank, or a tank containing a mutually compatible cargo; have separate pumping and piping systems that should not pass through the other cargo tanks unless encased in a tunnel; and have separate tank venting systems.
- Cargo piping should not pass through any accommodation, service, or machinery space other than cargo pump rooms or pump rooms.
- Pumps, ballast lines, vent lines, and other similar equipment serving as permanent ballast tanks should be independent of similar equipment serving as cargo tanks.
- Bilge pumping arrangements for cargo pump rooms or for hold spaces in which independent cargo tanks are installed should be situated entirely within the cargo area.
- Cargoes should not be carried in either the fore or aft peak tanks.
- Accommodation and service spaces and control stations should not be located within the cargo area.
- Cargo tanks and pumping arrangements should not be located within accommodation or machinery spaces.
- Tanks and piping systems for the well stimulation plant should be separated from the machinery and ship piping systems.
- Unless they are at least 7 m away from the cargo area containing flammable products, entrances, air inlets, and openings to accommodation, service, and machinery spaces and control stations should not face the cargo area.
- Where not bounded by a bottom shell plating, fuel oil tanks, a cargo pump room, or a pump room, the cargo tanks should be surrounded by cofferdams.
- For access to all spaces, the minimum spacing between the cargo tank boundaries and the structures of an adjacent ship should be 600 mm.
- Independent pressure tanks should be fitted with pressure-relief devices that are designed to direct the discharge away from personnel.
- Deck spills should be kept away from accommodation and service areas by using a permanent coaming of suitable height and extension.

- Remote control of the well stimulation processing plant should be performed from a position outside the area where the well stimulation systems are located.
- Enclosed spaces containing tanks, piping, pumps, and blenders for uninhibited acid should have entrances directly from the open deck or through air locks from other spaces. The air locks should have independent mechanical ventilation.

In many cases, well stimulation vessels have other additional functions, such as fire-fighting vessels, offshore supply vessels, and crane vessels. Some well stimulation vessels have a complicated arrangement with a double-deck well stimulation area configuration, which is similar to the topside of the FPSO. These configurations require extra design consideration with regard to ventilation, fire and gas detection, the effective fixed firefighting system, and safe escape and evacuation.

The following are additional design considerations that should be implemented and considered and that are not clearly addressed in IMO A.673(16) **[6]** and the Classification Society's rule requirements **[13][14]**.

- The location of the ventilator duct inlet and outlet in the enclosed cargo area should be carefully considered according to the arrangement of equipment and the area of stagnant gases.
- Oil-fired equipment should be outside the hazardous area; otherwise, efficient safety measures (such as insulation and distance) based on risk analysis should be considered.
- The efficient layout of fire and gas detectors should be considered according to mapping study, the hydrocarbon and chemical vapor stagnant areas, the location of the ventilator ducts (inlets and exhaust), and the characteristics of the gases (such as the density and molecular weight).
- If a deck crane is installed, the operation and service areas should be considered to avoid accidental events due to objects being dropped in well stimulation areas, as well as the escalation of accidental scenarios.
- Safe egress and escape routes may be limited by the narrow breadth and low height in certain spots and passageways due to the complex equipment, piping, and vent arrangement in the well stimulation vessel, which is small by nature and has insufficient space in the cargo area. Clear and sufficient escape routes are important for personnel safety during accidental events. Careful escape-route evaluation should be performed at the early design stage.
- Semi-enclosed spaces with openings for well stimulation equipment on deck, where the area is large enough to affect the stability of the vessel, should be considered for freeing ports against green water ingress into the spaces.
- All of the mechanical equipment and facilities that generate sparks should be situated outside hazardous areas.
- Cargo pump room entrances should be on the open deck (to the extent that is practical).

3.2 Active and passive fire protection system

The basis of the fire protection system in well stimulation vessels is presented in Chapter II-2 of the 1974 SOLAS Convention, as amended **[8]** IMO A.673(16) **[6]** the Classification Society's rules **[13][14]** and the Flag Administration requirements. Passive fire protection should also be arranged according to the rules and regulations, e.g., SOLAS Ch. II-2 **[8]**, the FSS Code **[9]**, and MODU 2009 **[21]**, to prevent or mitigate the serious consequences of a fire.

The following provisions apply for the carriage of flammable liquids, which is addressed in IMO A.673(16) **[6]**.

- During cargo transfer, the water pressure should be maintained in the fire main system.
- Fire hoses fitted with approved dual-purpose nozzles (i.e., spray/jet type with shutoff) should be attached to each fire hydrant in the vicinity of the flammable liquid to be carried.
- The cargo pump room where flammable liquids are handled should be equipped with a fixed fire-extinguishing system in accordance with 11.2 of the International Bulk Chemical Code.
- Either a fixed deck foam system or a fixed fire-extinguishing system of the dry chemical type to protect the deck within the cargo area is to be provided.

DNV GL has the following additional requirements under the classification notation LFL **[24]**.

- The vessel shall have a fixed foam fire-extinguishing system for protection of the cargo deck area. Application rate shall be not less than

  a) 5 litres/minute/m^2 with sufficient supply for at least 20 minutes, applicable for return mud or when carriage of liquids with flashpoint not lower than 43 ℃.

b) 10 litres/minute/m^2 with sufficient supply for at least 20 minutes, applicable for products covered by the IBC Code or methanol or when carriage of liquids with flashpoint below 43 ℃.

- The main control station for the system shall be suitably located outside of the cargo area, adjacent to the accommodation spaces, and readily accessible and operable in the event of fires in the areas protected.
- In addition, the vessel should carry in a readily available position, at cargo deck level, four portable foam applicator units with at least 8 portable 20 litres containers with foam concentrate, for use with water supplied by the vessel fire main.
- Two firefighter's outfits shall be provided, in addition to those required by SOLAS Reg. II-2/10.10.

In addition to the foregoing, the following principles should be considered in design.

- A water supply to the fixed foam fire-extinguishing system shall be in addition to the water supply required for the vessel’s fire main.
- Foam monitors requiring manual operation shall be positioned outside of the protected area and be readily available in the case of a fire in the protected area.
- There may be many blind sectors that cannot be covered by the foam monitors owing to the complex well stimulation equipment arrangement, height of equipment near the monitors, double deck configurations, etc. Accordingly, a combination of monitors and nozzles to cover the entire well stimulation area, including parts that might be overlooked, should be considered in initial design.
- Containerized power packs and equipment that generate >375 kW shall be arranged with the fixed firefighting system together with detection connected to the fire detection and alarm system of the vessel.

3.3 Fire and gas detection system

IMO A.673(16) **[6]**, DNV GL **[13][24]**, and ABS **[14]** specify the following requirements for fire and gas detection system and control actions.

- Spaces containing installations of uninhibited acids are to be provided with vapor-detection and alarm systems for hydrogen and hydrogen chloride gases **[6][13][14]**.
- Spaces containing tanks and piping for liquid nitrogen are to be equipped with an oxygen-deficiency monitoring system **[6][13][14]**.
- Spaces housing equipment and storage tanks for the well stimulation system are to be provided with a detection and alarm system for liquid leakage **[13][14]**.
- At least two portable instruments for detecting the flammable vapor concentrations should be provided in the case of cargoes with a flashpoint not exceeding 60 ℃ (closed cup test) are carried **[6][14][24]**.
- At least two portable instruments suitable for measuring the concentration of oxygen in the atmospheric air should be provided **[6][14][24]**.

For LFL cargo handling, the following design aspects should be considered **[24]**.

- Cofferdams surrounding LFL cargo tanks shall be fitted with gas detection or fitted with leakage detection. Alarm shall be provided at a manned control station.
- Arrangements shall be made to facilitate the measurement of the gas concentration in all tanks and other compartments within the cargo area.
- The cargo pump room shall be provided with a system for continuous monitoring of the concentration of hydrocarbon gases in accordance with SOLAS II-2 Reg. 4.5.10.1.3.

In addition, the followings are recommended to improve the safety and efficiency of the fire and gas detection design and arrangement which are not addressed in IMO A.673(16) **[6]** or Classification Society’s rules **[13][14]**.

- The recommended gas and fire detector location should consider the locations of potential leak sources, pressure, rates, density, equipment arrangement, and ventilation duct arrangement.
- For regular testing and maintenance, gas detectors should be located at easily accessible locations, to the extent that is practical.
- It is recommended to apply 2ooN voting concept which means among N number of detectors, minimum two detections are required to operate and comply with safety functions, considering the situation of malfunctioning of one of detectors.
- If an area is equipped with minimal detectors, it is essential

to consider a faulty detector as a positive alarm to maintain effective detection for this area and provide an indication in the control room that the alarm is faulty.

- Smoke detectors should be installed at or near the ventilation extract. It also needs to be considered gas detectors placed inside pump-room ventilation exhaust ducts and accommodation air intakes, if air intakes at these locations are near the well stimulation area.
- In many cases of temporary mobilization projects for well stimulation operation, the arrangement of the fire detection and alarm system in containerized power packs and machinery, which have risks of fire, and manned work spaces (e.g., labs and the control cabin) in the well stimulation operation area is overlooked. This fire detection and alarm system should be connected to the fire detection and alarm system of the vessel.
- Procedures should be developed to ensure that the detection system is regularly inspected and calibrated.
- The fire detection system, where electrically supplied, should be fed automatically from an emergency source of power by a separate feeder if the main power source fails.

3.4 Electrical installations and hazardous-area control

Electrical installations should satisfy the requirements of Chapter 10 of the International Bulk Chemical Code. **[7]**. The electrical equipment and components shall be a certified and an approved type for their intended service and hazardous-area location. API RP 505 **[25]** and IEC 60092-502 **[17]** provide relevant hazardous-area criteria for the installation of electrical equipment. Separation between hazardous well stimulation areas and nonhazardous areas, such as the engine room and accommodation space, is important for eliminating sources of ignition and accidental events.

The following are recommendations for hazardous-area control in well stimulation areas.

- Material selection to limit ignition and sparks should be reflected in the design. Non-sparking or spark-proof tools and instruments are to be used for all hazardous areas, such as the well stimulation area and pump room.
- In the case of enclosed spaces containing acid tanks and the pumping arrangement, equipment that is certified as safe for operation in a hydrogen/air atmosphere shall be used **[13]**.
- Penetration (e.g., cables, pipes, or shafts) between hazardous and nonhazardous areas should be limited or avoided. If such penetration is unavoidable, preventive measures against leaks to the nonhazardous areas should be identified, and a relevant risk study and measures should be performed.
- Operational procedures should be established to limit the use of non-ex-proof-type equipment during access to the well stimulation areas and pump rooms.
- All vent outlets from the well stimulation system and pump room ventilators shall be located in a safe area and shall be kept a sufficient distance from ignition sources, accommodation spaces, control spaces, and machinery space ventilation inlets. The air inlets for machinery spaces, accommodation spaces, and control spaces shall have a sufficient distance from the hazardous-area boundary.
- Where necessary, spark proof-type paints should be applied on steel gratings and the pump room floor to avoid accidental ignition caused by dropped objects.

3.5 Pump-room ventilation and cargo-tank vent system

The ventilation arrangement is important for ensuring a hydrocarbon- and flammable gas-free environment in the cargo handling space. The ventilation system should eliminate areas of stagnant gases within the space to provide a non-flammable environment.

IMO A.673(16) **[6]**, DNV GL **[13][24]**, and ABS **[14]** specify the following key requirements for pump-room ventilation and the cargo-tank ventilation system.

- The requirements for the ventilation of spaces in the cargo area specified in Chapter 12 of the International Bulk Chemical Code apply. However, the administration may grant relaxations concerning the distances required in 12.1.5 of the Code **[6]**.
- Independent pressure tanks should be fitted with pressure-relief devices that are so designed as to direct the discharge away from personnel **[6][13][14]**.
- Cargo-tank vent systems of integral or independent gravity tanks should satisfy the requirements specified in Chapter 8 of the International Bulk Chemical Code, except that the height specified in 8.3.4 of the code may be reduced to 2 m **[6]**.
- Outlets from safety valves of nitrogen tanks are to be led to open deck **[13][14]**.
- Ventilation of spaces for acid storage and handling: Local exhaust ventilation is generally preferred. Explosion-proof

electrical equipment is to be used for ventilating spaces containing acetic acid. The spaces containing uninhibited acid are to have independent mechanical ventilation with a capacity of minimum 30 air changes per hour, while those containing inhibited acid a minimum of 20 air changes per hour. The discharge suctions are to be located both, at floor and ceiling levels of the space concerned **[14]**.

- Spaces containing installations for the storage or handling of acid shall have an independent mechanical ventilation with a capacity of minimum 30 air changes per hour **[13]**.
- Ventilation of spaces for the storage and handling of dry or liquid additives will be case-by-case considered based on flammability, toxicity, and reactivity criteria of the additives concerned **[14]**.
- Spaces containing installations for liquid nitrogen shall have mechanical ventilation with a capacity of minimum 20 air changes per hour, independent from the ventilation system for the accommodation space **[13][14]**.
- Vent outlets from acid tanks shall be lead to the open deck. The outlets shall have a minimum height of 4 m above the deck and located at a minimum horizontal distance of 5 m from the openings to the accommodation and service spaces **[13][14]**.
- The vent outlets from the acid tanks shall have pressure/vacuum valves The outlets shall be provided with flame screens **[13][14]**.

In addition, the following are recommended as best engineering practices.

- The ventilation system should have a redundancy system and procedures in place to ensure that the system has minimal downtime in the case of one-fan failure. In this aspect, minimum of two (2) ventilation fans should be provided for the pump room and large enclosed well stimulation.
- The vent fan design should have non-spark fan blades or have a sufficient blade tip clearance.
- The pump-room ventilation exhaust fans should maintain ventilation if a gas-detection scenario exists within the pump room.
- An open-type grating and platform should be installed within the space to ensure proper air circulation and avoid the accumulation of stagnant gases below the platform.
- Pump-room extractor fans, including impellers, shafts, and gas seals, should be inspected on a regular basis.

3.6 Process and piping system, and other safety design

Although the design follows the applicable Classification Society requirements and IMO A.673(16) **[6]**, there are areas in which the cargo handling design can be improved to enhance the safety of the well stimulation vessel. Among others, the followings are some of the key requirements of the Classification Society **[13][14][24]** and IMO A.673(16):

- The cargo transfer system should comply with the requirements specified in Chapter 5 of the International Bulk Chemical Code or Chapter 5 of the International Gas Carrier Code when considered applicable and practical by the Administration, taking into account existing industry standards and practices **[6]**.
- The remote shutdown devices for all cargo pumps and similar equipment should be capable of being activated from a dedicated cargo control location that is manned at the time of cargo transfer and from at least one other location outside the cargo area and at a safe distance from it **[6][13][14]**.
- Deck cargo and products covered by IMO A.673(16) should not be loaded or unloaded simultaneously **[6]**.
- Generally, piping conveying well stimulation substances is to be joined via welding, except as allowed in the rules. Storage tanks, pumps, valves, gaskets, and piping for uninhibited acids are to be of corrosion-resistant materials or are to have internal lining of corrosion-resistant materials **[13][14][24]**. Flanges or other detachable pipe connections should be covered with spray shields as necessary.
- Tanks and piping systems for the well stimulation processing plant are to be separated from the vessel's marine machinery and piping systems **[6][13][14]**.
- Where auxiliary energy is required for the functionality of emergency control and shutdown, a reliable power supply is to be provided. Electrical power supply is to be from a main power system and from a monitored uninterrupted power supply (UPS) capable of continuously operating for at least 30 minutes upon loss of power from the main source. The UPS is to be powered from both the main and the emergency power systems. Where hydraulic and/or pneumatic power supply is used for actuation of emergency control and shutdown, duplication arrangements are to be made. Where driving power for hydraulic and/or pneumatic pumps is electric, power-supply circuits are to be connected

to the main and emergency power sources separately **[14]**.
- Each well injection line is to be provided with a check valve located at a flow head or a test tree **[14]**.
- Cargoes which react in a hazardous manner with other cargoes shall have separate pumping and piping systems **[6][13][14]**.

In addition, the following are recommended to ensure the safety of the well stimulation cargo piping and safety system.

- Spray arresters should be provided around the glands of all rotary cargo pumps in order to reduce the formation of oil mists in the event of minor leakage from the gland.
- Control and condition monitoring of the system should be performed at the control station to detect abnormal conditions, and necessary actions should be taken.
- High-pressure pumps should be fitted with safety relief valves.
- At least one isolation valve should be installed at high-pressure manifold inlets and outlets in order to isolate the line, if necessary.
- Pipe stress and flexibility analysis should be performed for high-pressure piping and cryogenic service piping.
- Hose assemblies for flammable fluids should be fire-tested according to IMO Res. A.753(18), API 16C, ISO 15540, ISO 15541, or an equivalent standard.
- Piping installations and hose couplings should be protected against damage due to handling operations.

3.7 Emergency shutdown system

The purpose of the emergency shutdown (ESD) systems in the event of abnormal conditions is to minimize the escalation of events and to minimize the extent and duration of such events. This is achieved by a combination of actions, including stopping of hydrocarbon flow and shutdown of equipment and systems to bring them to a predefined safe state **[5]**. Shutdown systems shall be so designed that the risk of unintentional stoppages caused by malfunction in a shutdown system and the risk of inadvertent operation of a shutdown are minimized **[21]**.

IMO A.673(16) **[6]**, DNV GL **[13][24]**, and ABS **[14]** specify the following requirements for the ESD system.

- Emergency stop of all pumps in the well stimulation system is to be arranged from one or more positions located outside the area for well stimulation operations **[13][14]**.
- Emergency shut-off valves are to be provided in liquid nitrogen lines from each nitrogen tank. The shut-off valves are to be remotely controlled from one or more positions outside the area for well stimulation operations **[6][13][14]**.
- Emergency depressurizing and disconnection of the transfer hose are to be arranged from the center control position and vessel position control station **[6][13][14]**.
- Where applicable, at least one ESD panel capable of closing all barrier elements of the blowout preventer and disconnection connector for subsea blowout preventer sections is to be provided at a safe and readily accessible location **[14]**.

The following should be considered in ESD philosophy and design.

- The ESD system should be designed to allow testing without interrupting other systems onboard.
- Systems, actuated devices, and controls shall be designed to fail-safe. This normally means that shutdown valves will “fail to closed” position.
- A cause-and-effect matrix should be developed and evaluated to determine the appropriate actions to be taken for isolating the ignition sources and shutting down the relevant equipment and systems. The ESD logic outlined and the philosophy behind the cause-and-effect matrix should be fully understood by crews.

3.8 Acid and cryogenic spill protection and safety design

Chemical or cryogenic liquid spillage can damage the hull and environment and endanger humans. For preventing such spillage, there are many design considerations, including material selection, leakage control using a shield, spill coaming or drip trays, and safe drainage. IMO A.673(16) **[6]** and Classification Society rules **[13][14]** specify as follows.

- Floors or decks under acid storage tanks and pumps and piping for acid should have a lining or coating of corrosion-resistant material extending up to a minimum height of 500 mm on the bounding bulkheads or coamings. Hatches or other openings in such floors or decks should be raised to a minimum height of 500 mm **[6][13][14]**;
- Flanges other detachable pipe connections should be covered by spray shields**[6][13][14]**.

- Portable shield covers for connecting the flanges of the loading manifold should be provided. Drip trays of corrosion-resistant material should be provided under loading manifolds for acids **[6][13]**.
- Spaces for acid storage tanks and acid pumping and piping should be provided with drainage arrangements of corrosion-resistant materials **[6][13]**.
- Deck spills should be kept away from accommodation and service areas by means of a permanent coaming of suitable height and extension **[6][14]**.
- Drip trays of acid-resistant material are to be provided under loading manifolds **[13][14]**.
- Spaces housing tanks, pumps, and piping for acids or additives shall have a separate drainage system not connected to the draining of the other areas, and this system is to be made of acid-resistant materials **[13][14]**.
- Drainage arrangements for pump rooms, void spaces, any slop tanks, double-bottom tanks, and similar spaces are to be situated entirely within the well stimulation processing area, except for void spaces, double-bottom tanks, and ballast tanks, where such spaces are separated from tanks containing well stimulation substances or residues of such substances by a double bulkhead **[14]**.
- Drip trays resistant to cryogenic temperatures are to be provided at manifolds transferring liquefied gases and at other flanged connections in the system **[13][14]**.
- Tanks for hydrochloric acid are to have a closed gauging system. A high-level alarm is to be provided. The alarm is to be activated by a level-sensing device independent of the gauging system **[14]**.
- The design of pumping and piping system for cryogenic system should refer to liquefied gas tanker rules (e.g., DNV GL-RU-Pt.5 Ch. 7 Sec. 5) **[13]**.
- Each enclosed space used for handling or storage of a liquefied gas should be fitted with a sensor continuously monitoring the oxygen content of the space and an alarm indicating low oxygen concentration **[6][13][14]**.
- Drip trays resistant to cryogenic temperatures should be provided at manifolds transferring liquefied gases or at other flanged connections in the liquefied gas system **[6][13][14]**.
- Tanks for liquefied nitrogen are to have gauging and level-detection arrangements **[6][13][14]**.

3.9 Chemicals and additives

In many cases, well stimulation vessels carry chemicals and additives that are not listed in the International Bulk Code **[7]**. Chemicals to be carried in bulk that are not classified by the IBC require tripartite agreements among the owner of the vessel the governments of the country of manufacturing or shipping and the country of receiving and the Flag Administration. This is to be assessed by the Administration and IMO as per MEPC.1/Circ. 512 Section 3 and Section 7 with the tripartite agreement. The process, along with the applicable forms are described in MEPC.1 Circ. 512. The assessment shall include IBC designations in accordance with the table in Chapter 17 of the IBC. Additives that fall outside the scope of products in IMO A.673(16) Sec. 1.2.2 may be carried in limited amounts in accordance with requirements acceptable to the Administration. The aggregate amount of such additives that may be transported should not exceed 10 % of the vessel's maximum authorized quantity of products subject to these guidelines. An individual tank should contain not more than 10 m^3 of these additives. However, each additive still needs operator's assessment for each of the chemicals, although it does not need to be subject to tripartite agreement.

3.10 Emergency response and personal protection

The design of the well stimulation vessel should include a safe and controlled emergency response to accidental events. The escape way shall be marked so that personnel can identify the routes of escape and easily find the escape exits. Safe, direct, and unobstructed exits, access, and escape routes should be provided from the well stimulation area to the safe area, muster areas, and embarkation or evacuation points. It is important to ensure that the escape routes are not blocked by equipment, such as piping and fittings. The surfaces of decks, walkways, platforms, stairs, ladder rungs, etc. should be non-slip and designed for drainage and easy removal of contaminants such as mud and oil. Communication and alarm systems should be provided to alert all personnel on board at any location of an emergency. The systems should be suitable to provide instructions for an emergency response. The alarms shall be clearly audible and easily distinguishable at all locations. In locations where machinery noise prevents the alarm from being heard, additional a visible means of alarm (e.g., rotating light) shall be provided.

The following should be considered as per IMO A.673(16) **[6]**, DNV GL **[13]**, and ABS **[14]**.

- A suitably marked decontamination shower and eyewash station should be available on deck at a convenient location. The shower and eyewash should be operable under all ambient conditions **[6][13][14]**.
- Protective and safety equipment should be kept on board in suitable locations, as required by Chapter 14 of the International Bulk Chemical Code or the International Gas Carrier Code for products to be carried **[6][13][14]**.
- Spaces containing tanks and piping for liquid nitrogen are to be equipped with an oxygen-deficiency monitoring system **[6][13][14]**.
- Spaces containing installations of uninhibited acids are to be provided with vapor-detection and alarm systems for hydrogen and hydrogen chloride gases **[13][14]**. Spaces containing equipment and storage tanks for the well stimulation system shall be provided with a detection and alarm system for liquid leakage.
- Hardwired means for voice communications are to be provided between the center control station for well stimulation operations and the vessel's position-keeping control stations **[14]**.

3.11 Operation manuals and procedures

Well stimulation vessels shall have an approved operation manual readily available on board. The manual shall give instructions and information on safety aspects related to well stimulation processing. Each ship certified to carry noxious liquid substances should be provided with a Cargo Record Book, a Procedure and Arrangements Manual, and a Shipboard Marine Emergency Plan developed for the ship in accordance with Annex II of MARPOL 73/78 **[15]** and approved by the Administration **[6][13]**.

4. Conclusion

Considering the nature of the operation profiles of well stimulation vessels, the potential risks associated with operations of well stimulation vessels are significantly high. The industry practice is to design the vessel in accordance with the project specifications and relevant mandatory rules and regulatory requirements, while minimizing the cost.

However, the rules and regulations defined by the project specifications may only provide a minimum safety level for well stimulation vessels therefore, additional design, safety, and company procedures should be considered to ensure safe operation of well stimulation vessels.

In this paper, numerous documents, rules, and guidelines were reviewed, and various design considerations, best engineering practices, and guidelines that are essential for reducing the risks of different well stimulation operations, including temporary assignments for non-purpose-built vessels, were addressed. These references and recommendations should be considered to the extent that they are practical and applicable to the existing and the for newbuilding design. The implementation of the items discussed herein is left to the operators, designers, builders, and corresponding authorities, based on principle of the sound engineering practice.

Disclaimer

The opinions expressed herein are solely those of the author and do not represent the views or opinions of the author's employer or any other parties.

Author Contributions

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