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Crude oil transfer safety analysis and oil spills prevention in port oil terminal

Keywords

oil port terminal, oil transfer, operation process, system reliability, oil spill, human factor, pressure upsurge, safety procedures, ESD System, LCH Simulator.

Abstract

The paper describes the problem of crude oil transfer in a port oil terminal and includes the safety analysis of this operation and analysis of potential causes and possible scenarios of oil spill events in a port terminal. The operation process of crude oil transfer is described and its statistical identification is given. The reliability and availability analysis of the system of crude oil transfer in a port terminal is performed. Moreover, analysis of crude oil transfer process taking into account the human factor is provided. The Fault Tree Analysis and sensitivity analysis for oil spill event in a port terminal is proposed to identify and analyse potential causes and possible scenarios of oil spill. Introducing methods for the prevention of oil spills, special attention is paid to safety procedures during liquid cargo transfer. Technical solutions used in oil terminals are described and recommendation regarding the Emergency Shutdown System are given. Additionally, associated safety systems, such as surge relief system, are described. Emphasizing the role of human factor in the process of crude oil transfer and its safety, trainings on the Liquid Cargo Handling Simulator are proposed to improve skills and knowledge of personnel on board and ashore.

1. Introduction

In the Baltic Sea region, there are many oil terminals, which perform transhipment of crude oil and refined petroleum products. Oil terminals are a key element of the petroleum supply logistics of crude oil to refineries and oil transit. The accident in the oil terminal during cargo operations may have a long or short-term consequences for the work of the terminal, that may be associated with the socioeconomic losses and environmental costs consequences.

Analysing the safety of crude oil transfer in a port terminal as a multidimensional problem, in the paper an approach focusing on a technical system analysis is presented, by performing the reliability and availability analysis of oil transfer system, as well as the analysis of crude oil transfer operation process, including the human factor. In the second of these approaches, a special attention is paid to the human factor and related regulations and procedures, based on Ship/Shore Safety Check List (SSSCL). It is extremely important to make people responsible for oil transfer in the terminal aware of possible spill threats and their consequences. Basic rules and procedures for dealing with specific situations during oil transfer between tanks and a terminal are given in the paper. The problem of assessing the situation, awareness of threats and making decisions may result from the lack of adequate training courses or insufficient their scope. Education and training of emergency procedures are of special importance. The ability to respond appropriately and quickly in critical situations during crude oil transfer is a crucial

factor for the oil terminal safety and it can be strengthened and improved by adequate training.
The results of crude oil transfer safety analysis, presented in this paper, are developed in the scope of the HAZARD project titled "Mitigating the Effects of Emergencies in Baltic Sea Region Ports". As a practical part of this study, to prevent oil spill during crude oil transfer in a port terminal, the training courses on the Liquid Cargo Handling Simulators (LCHS) are proposed. Utilization of the simulators is a simple and safety option to improve skills in controlled conditions. These courses show the procedure and operations handling different situations during the crude oil transfer, both for the terminal operators and the tanker operators, and are attached to the project report in the form of movies.
One of important causes of oil spill is a pressure upsurge inside pipelines as a hydraulic hammer's consequence. These pressure surges can be generated by anything that causes the liquid velocity in a line to change quickly e.g., valve closure, pump trip, Emergency Shut Down (ESD) closure occurs and subsequently packing pressure. The particular attention is paid to the pressure upsurge inside pipelines caused by sudden valve closure on an oil transfer installation in port terminal.

2. Operation process of the crude oil transfer inside the pipeline system and its statistical identification

The operation process of crude oil transfer has an influence on the oil terminal safety and environment safety. To describe this influence, we start with constructing a general model of its operation process. For the oil terminal during its operation process $Z(t)$, $t \in (0,+\infty)$, we distinguish following $\nu = 9$ operational states [4]:

z_1 − loading cargo with initially slow rate,
z_2 − laboratory tests of exported crude oil,
z_3 − loading cargo with full rate,
z_4 − loading cargo with reduced rate,
z_5 − unloading cargo with initially slow rate,
z_6 − unloading cargo with full rate,
z_7 − unloading cargo with reduced rate,
z_8 − terminal idle mode, there is no transfer of cargo,
z_9 − internal recirculation process.

In all operational states, system has the same structure described in Section 5.

2.1. Description of processes related to the crude oil transfer inside the pipeline system

We describe below all listed operational states of the crude oil transfer process specifying technical parameters.

First, a tanker arriving oil terminal have to be properly moored for cargo handling process and its position has to be continuously controlled during the whole time of the cargo operations. Moreover, the ship's and the terminal's representatives have to discuss all technical issues and procedures before the transhipment process may begin.

Figure 1. Loading arms connected to the tanker in the oil terminal [26].

To start the crude oil loading process a piping system line up agreement between tank farm and terminal and between vessel and terminal have to be set. Before tanker loading cargo from the oil terminal, the vessel manifold and loading arms are connected, for crude oil usually 1 or 4 arms are connected (Fig. 1). Next the lines are line up choosing dedicated tanks and pumps ashore and by opening or closing relevant line's valves. Oil terminal leaves per one valve closed on each loading arm. After receiving readiness confirmation for starting loading process from the tanker, the last valves on marine loading arms are opened and the process of crude oil loading with initially slow rate begin (state z_1). Cargo starts to flow due to gravity, if needed the pumps start to obtain agreed initial rate. Initial loading rate on beginning loading operation avoid to create the static electricity in the cargo tank and increase VOC (Volatile Organic Compounds) production.
Technical parameters (pinpoint loading parameters) during initial state of crude oil loading include inter alia:

- initial rate – bottom splashing (usually abt. 1000 cbm/h),
- pressure 1 – 5 bars,
- temperature max 35°C.

Initial loading rate should be kept till the last cargo tank is filled up to the level of drop line to avoid turbulent flow in empty tank. Also, the sounding more than 0.30m allowed to draw the samples of cargo for laboratory test from all tank using hermetic sampler device.
After some laboratory tests of exported crude oil (state z_2) and relevant checks on cargo tanks and cargo pipelines against leakages and aberrations, the oil terminal receive agreement from the vessel to

increase loading rate to agreed maximum rate and the process of loading crude oil with full rate start (state z_3). During loading operations, the parameters and infrastructure integrity have to be inspected on a regular basis and tanker receives cargo from the terminal in accordance with agreed parameters (pressure, temperature, loading rate).

Below there are given monitored technical parameters of crude oil loading process during state z_3:

- maximum loading rate 1000 – 10000 cbm/hrs (depend on tanker size and her venting arrangement),
- loading pressure 3 – 4 bars,
- temperature max 35°C.

Tanker's tanks are loaded usually to their 95-98% capacities. Final stage of each tank's filling is named "topping off". On this stage, for oil spill avoidance reasons, loading rate is decreased to maximum loading rate for single cargo tank, generally for tanker VLCC size approx. 1000 cbm/h (state z_4). When one tank is already full other tank goes to open position to let the cargo pass inside, then the topping up tank is closed. When the last cargo tank is topped up, tanker inform oil terminal for pump stoppage and valve closure. When this happens, terminal gives confirmation regarding stoppage and the ships manifold valves are closed. When tankers and terminal's valves on loading lines are closed and cargo from pipelines is drained back to shore installation oil terminal goes into idle mode (state z_8).

Technical parameters in the final stage of crude oil loading process are:

- topping up rate (usually 1000 cbm/h),
- pressure 1 – 2 bars,
- temperature max 35°C.

Parameters of planned cargo operations stoppages (ex. Line Displacement; First Foot Sample) are:

- initial rate – bottom tank splashing (usually abt. 1000 cbm/h),
- maximum pressure limits 1 bars,
- cargo temperature limits 1 – 35°C.

The process of crude oil discharging is similar. Before starting the unloading process, a piping system line up agreement between tank farm and terminal and an agreement between vessel and terminal have to be set. Then, the tanker's manifold and loading arms are connected; during unloading process for crude oil usually 3 loading arms are connected. The line has to be line up by choosing dedicated tanks and pumps on vessel and by opening or closing relevant line's valves. After fixing the readiness notice between vessel, oil terminal and tank farm, the loading process from the tank farm starts. The last valves on marine loading arms are opened and the pumps on vessel start with initial discharging rate (state z_5). Initial discharging rate allowed to slowly heave up the floating roof in shore cargo tanks and also make the slack in all cargo tanks below 95% of volume to improve the safety during operation.

Next, if there are no aberrations, after obtained from terminal confirmation, tanker increase discharging rate to agreed maximum rate, the unloading cargo starts with full bulk discharging rate (state z_6). During discharging the parameters and infrastructure integrity have to be inspected on a regular basis. In a simplistic way, in the final stage the unloading cargo with reduced rate takes place and tanker finishes discharging cargo, by stripping all cargo tanks one by one (state z_7).

During bulk discharging or at the end of the transfer cargo we are dealing with the process of washing cargo tanks COW (Crude Oil Washing) to reduce the clingage from the vertical part of dedicated cargo tank and the bottom sediment. Then the cargo pumps stop, relevant valves on main cargo lines are closed and begin the stripping operation, all liquids from cargo tanks are collected in Slop tank. After internal stripping cargo residue from Slop tank is transferred through the special dedicated SD (Small diameter) line directly to loading arm by passing main tanker's pipelines. After that the loading arms are disconnected.

Below there are given technical parameters of crude oil discharging process.

During the state z_5:

- initial discharging rate (usually 1000 cbm/h) – to perform "safety ullages" in cargo tanks,
- pressure 1 – 5 bars,
- temperature max 35°C,

during the state z_6:

- maximum bulk discharging rate (usually approx. 10000 cbm/h),
- pressure 3 – 10 bars, generally depend on shore tank capacity and its location,
- temperature max 35°C,
- planned cargo operations stoppages (ex. Line Displacement,) in the state z7:
- maximum pressure limits 10 bars,
- cargo temperature limits 1 – 35°C.

To start the internal recirculation process (state z_9) a piping system line up agreement between tank farm and terminal has to be set. Relevant valves are opened or closed; one valve on each tank has to be still closed. After confirming readiness of both sides, i.e. terminal and tank farm, the valves on dedicated tanks are opened and the recirculation by gravity commences. Next, relevant checks against line integrity and aberrations are made and cargo pumps start. During recirculation, the parameters and infrastructure integrity have to be also inspected on a regular basis. When the process of recirculation is finished the pumps stop and the line valves are closed.

Technical parameters of internal recirculation of crude oil are:

- recirculation rate 5000 cbm/h,
- maximum pressure limits 10 bars,
- cargo temperature limits 1 – 35°C.

In terminal idle mode, there is no transfer of cargo, however cargo is still inside shore pipelines.

2.2. Statistical identification of the system operation process

The following basic operation process statistical data are fixed [16]:

- the number of the system operation process states $\nu = 9$;
- the system operation process observation/ experiment time $\Theta = 61$ days;
- the number of the system operation process realizations $n(0) = 2$;
- the vector of realizations of the numbers of the ship-rope elevator operation process transitions in the particular operation states z_b at the initial moment $t = 0$

$$[n_b(0)] = [0,0,0,0,0,0,0,2,0]; \qquad (1)$$

- the matrix of realizations n_{bl} of the numbers of the system operation process transitions from the state z_b into the state z_l during the experiment time $\Theta = 61$ days

$$[n_{bl}] = \begin{bmatrix} 0 & 5 & 5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 9 & 0 & 0 & 0 & 9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 \\ 5 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}; \qquad (2)$$

- the matrix of realizations of the total numbers of the system operation process transitions from the operation state z_b during the experiment time $\Theta = 61$ days

$$[n_b] = [10,14,5,5,18,9,9,15,1]. \qquad (3)$$

On the basis of the above statistical data it is possible to evaluate the vector of realizations

$$[p(0)] = [0,0,0,0,0,0,0,1,0]. \qquad (4)$$

of the initial probabilities $p_b(0)$, $b = 1,2,\ldots,9$, of the system operation process transients in the particular states z_b at the moment $t = 0$

- the matrix of realizations

$$[p_{bl}] = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{5}{14} & 0 & 0 & 0 & \frac{9}{14} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \frac{1}{2} & 0 & 0 & 0 & \frac{1}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ \frac{5}{15} & 0 & 0 & 0 & \frac{9}{15} & 0 & 0 & 0 & \frac{1}{15} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \qquad (5)$$

of the transition probabilities p_{bl}, $b,l = 1,2,\ldots,9$, of the system operation process from the operation state z_b into the operation state z_l during the experiment time $\Theta = 61$ days.

On the basis of the statistical identification of system operation process we obtain the preliminary set of realizations of the system operation process conditional sojourn times θ_{bl}, $b,l = 1,2,\ldots,9$, $b \neq l$, in the state z_b, while the next transition is to the state z_l during the experiment time $\Theta = 61$ days.

Subsequently, the conditional mean values $M_{bl} = E[\theta_{bl}]$, $b,l = 1,2,\ldots,9$, $b \neq l$, of the lifetimes in the particular operation states have been estimated [16]:

$$M_{12} = 0.50,\ M_{13} = 0.32,\ M_{21} = 3.10,\ M_{25} = 2.99,$$

$$M_{34} = 19.57,\ M_{48} = 0.51,\ M_{52} = 0.49,\ M_{56} = 0.33,$$

$$M_{67} = 19.72,\ M_{78} = 0.59,\ M_{81} = 49.40,$$

$$M_{85} = 59.00,\ M_{89} = 106.00,\ M_{98} = 24.00 \text{ hours.}$$

Hence, using the results given in [16], the unconditional mean sojourn times in the particular operation states are:

$$M_1 = E[\theta_1] = p_{12}M_{12} + p_{13}M_{13} \cong 0.41,$$

$$M_2 = E[\theta_2] = p_{21}M_{21} + p_{25}M_{25} \cong 3.03,$$

$$M_3 = E[\theta_3] = p_{34}M_{34} = 19.57,$$

$$M_4 = E[\theta_4] = p_{48}M_{48} = 0.51,$$

$$M_5 = E[\theta_5] = p_{52}M_{52} + p_{56}M_{56} \cong 0.41,$$

$$M_6 = E[\theta_6] = p_{67}M_{67} = 19.72,$$

$$M_7 = E[\theta_7] = p_{78}M_{78} = 0.59,$$

$$M_8 = E[\theta_8] = p_{81}M_{81} + p_{85}M_{85} + p_{89}M_{89} \cong 58.93,$$

$$M_9 = E[\theta_9] = p_{98}M_{98} = 24.00 \text{ hours.} \qquad (7)$$

Since from the system of equations below [16]

$$\begin{cases} [\pi_b] = [\pi_b][p_{bl}] \\ \sum_{l=1}^{9} \pi_l = 1, \end{cases}$$

where $[\pi_b] = [\pi_1, \pi_2, \ldots, \pi_9]$ and matrix $[p_{bl}]$ is given by (5), we get

$$\pi_1 = 0.1194,\ \pi_2 = 0.1636,\ \pi_3 = 0.0597,$$

$$\pi_4 = 0.0597,\ \pi_5 = 0.2077,\ \pi_6 = 0.1038,$$

$$\pi_7 = 0.1038,\ \pi_8 = 0.1709,\ \pi_9 = 0.0114. \qquad (8)$$

The limit values of the transient probabilities $p_b(t)$ at the operational states z_b, from [16], are given by

$$p_1 = 0.0034,\ p_2 = 0.0347,\ p_3 = 0.0818,$$

$$p_4 = 0.0021,\ p_5 = 0.0060,\ p_6 = 0.1433,$$

$$p_7 = 0.0043,\ p_8 = 0.7052,\ p_9 = 0.0192. \qquad (9)$$

Finally, using the limit values of the transient probabilities $p_b(t)$ we obtain the sojourn times $\hat{\theta}_b$ of the system operation process $Z(t)$ in particular operational states z_b, $b = 1, 2, \ldots, 9$. Based on the received probabilities, given by (9), for operation time $\theta = 365$ days, we determine the expected values of the system operation process total sojourn times $\hat{\theta}_b$ in particular operation states z_b, $b = 1, 2, \ldots, 9$, and they respectively are

$$E[\hat{\theta}_1] = p_1\theta \cong 1.24 \text{ days,} \qquad (10)$$

$$E[\hat{\theta}_2] = p_2\theta \cong 12.67 \text{ days,} \qquad (11)$$

$$E[\hat{\theta}_3] = p_3\theta \cong 29.86 \text{ days,} \qquad (12)$$

$$E[\hat{\theta}_4] = p_4\theta \cong 0.77 \text{ day,} \qquad (13)$$

$$E[\hat{\theta}_5] = p_5\theta \cong 2.19 \text{ days,} \qquad (14)$$

$$E[\hat{\theta}_6] = p_6\theta \cong 52.30 \text{ days,} \qquad (15)$$

$$E[\hat{\theta}_7] = p_7\theta \cong 1.57 \text{ days,} \qquad (16)$$

$$E[\hat{\theta}_8] = p_8\theta \cong 257.40 \text{ days,} \qquad (17)$$

$$E[\hat{\theta}_9] = p_9\theta \cong 7.01 \text{ days.} \qquad (18)$$

3. Scenarios and classification of accidents during crude oil transfer process

For this paper needs, we divided oil related incidents into three types: oil leakage, overflow and the most dangerous oil spill [4]. Types of accidents are concerned with the volume of oil spilled and are strictly related to the states of the operational process (Fig. 2):

- oil leakage – incident, that may occur during the state z_1, z_2, z_5, z_8 and z_9,
- oil overflow – incident something between leakage and spill, that may occur during the state z_4 and z_7,
- oil spill – incident, that may occur during the state z_3 and z_6.

Most incidents related to the transmission of crude oil concern leakages and they are included in this group of accidents.

The transient probabilities of system being in particular operational states (9) may allow estimating the probability of creating situations of potential threats of oil leakage, oil overflow and spill. For example, the likelihood of a sudden oil spill is much smaller than the likelihood of oil leakage because it can only occur during the phase of oil transfer with full rate. Of course, an uncontrolled oil leakage or overflow may turn into an oil spill, so detailed analysis of the crude oil transfer is needed to estimate the likelihood of oil spill threats.

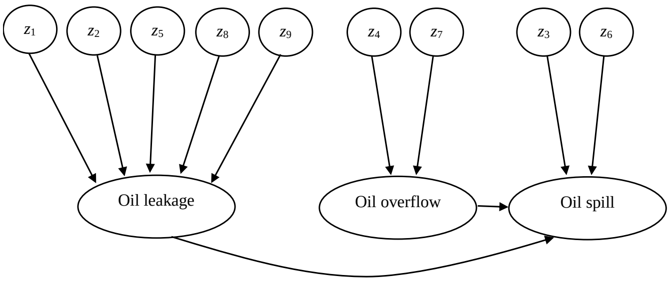

Figure 2. Spill incidences in terms of oil transfer operational states.

Next, considering the expected values of the system operation process total sojourn times $\hat{\theta}_b$ in particular operation states z_b, $b = 1, 2, \ldots, 9$, during operation time $\theta = 365$ days, given by (10)-(18), and classification of oil spill incidences in terms of oil transfer operational states, we estimate the expected values of time of occurrence of the potential danger of oil spill incidents from the crude oil transfer system. Namely, the expected values of time of occurrence of the potential oil leakage hazard from the system is

$$E[\hat{\theta}_{oil\_leakage}] = E[\hat{\theta}_1] + E[\hat{\theta}_2] + E[\hat{\theta}_5] + E[\hat{\theta}_8] + E[\hat{\theta}_9] \cong 280.50 \text{ days}, \quad (19)$$

the expected values of time of occurrence of the potential oil overflow hazard from the system is

$$E[\hat{\theta}_{oil\_overflow}] = E[\hat{\theta}_4] + E[\hat{\theta}_7] \cong 2.34 \text{ days}, \quad (20)$$

and the expected values of time of occurrence of the potential hazard of direct and sudden oil spillage from the system is

$$E[\hat{\theta}_{oil\_spill}] = E[\hat{\theta}_3] + E[\hat{\theta}_6] \cong 82.16 \text{ days}, \quad (21)$$

during operation time $\theta = 365$ days.

The main causes of oil leakage and oil spill include:

- disconnecting the ship's manifold from the loading arm during the transhipment due to technical drawbacks or human error (defect) in connecting the arm to the manifold;
- hydraulic impact due to a sudden valve closure on the ship in case of loading, or a valve closure at the terminal in case of unloading from the ship.

For example, PDVSA, oil company in Venezuela, confirmed that a crude spill occurred from a pipeline, on March 28th, 2017. The crude oil leak was a result of a break in the line running from a crude terminal to a single buoy mooring, but it did not affect terminal operations though [28].

Oil overflow may be the result of no stopping loading onto the ship at the proper time. Then, the overflowing of cargo tanks and oil spills with P/V valves or mast raiser may occur. As a consequence of inadequate level monitoring the gasoline tank was overfilled in Buncefield, UK, in 2005. The overflow occurred due to the defect of the monitoring system that should detect a high level and shut-off the inflow. During that incident, more than 250 000 litters of gasoline was spilled from an atmospheric pressure storage tank [14]. Oil overflow on shore storage tank can happen also during ship discharging.

Oil spill on board of the ship or on oil terminal pipelines may occur during transfer cargo with full rate, but uncontrolled oil leakage can also result in oil spill and pollution of marine ecosystems. For example, the bunker barge spilled about 70 tons of fuel at the ATB Vitol oil terminal in Malaysia on August 24, 2016. The spill occurred as the result of a leaking hose during bunkering of the vessel [24].

According to “Oil Tanker Spill Statistics 2016”, oil spills during loading and discharging account for 40% of all small sized spills (below 7 tonnes), classified by operation at time of incident, in 1974-2016. In medium sized spills (7-700 tonnes), 29% occurred during loading and discharging operations. Large spills during oil transfer operations are less frequent and account for 9% of all incident recorded in 1970-2016. Considering these large spills in terms of cause, it can be noticed that 31% are caused by fire or explosion, 26% by equipment failure and 19% by other causes that include heavy weather damage and human error [13].

4. Oil spill threats related to crude oil transfer in the terminal

Considering the causes and circumstances of oil spills during oil transfer operations we propose in this paper classification for internal and external reasons (Fig. 3).

Internal causes may include:

- technical conditions of oil terminal's infrastructure,
- technical conditions of equipment and systems on tanker vessels,
- human error made by vessel or terminal workers involved in the transhipment process.

Causes associated with technical conditions of oil terminal's infrastructure may include failure of different systems: main oil line, flow line, arms, hoses, hose joints, flange joints, block valves. They can depend on various factors, such as, insufficient maintenance level of pipes, devices, technological appliances and sensors, carried out hot works in sensitive areas. Among human errors we mention errors made during technological process, maintenance and other activities, abstractedness or measurement errors, errors in setting valves or errors related to insufficient technological knowledge.

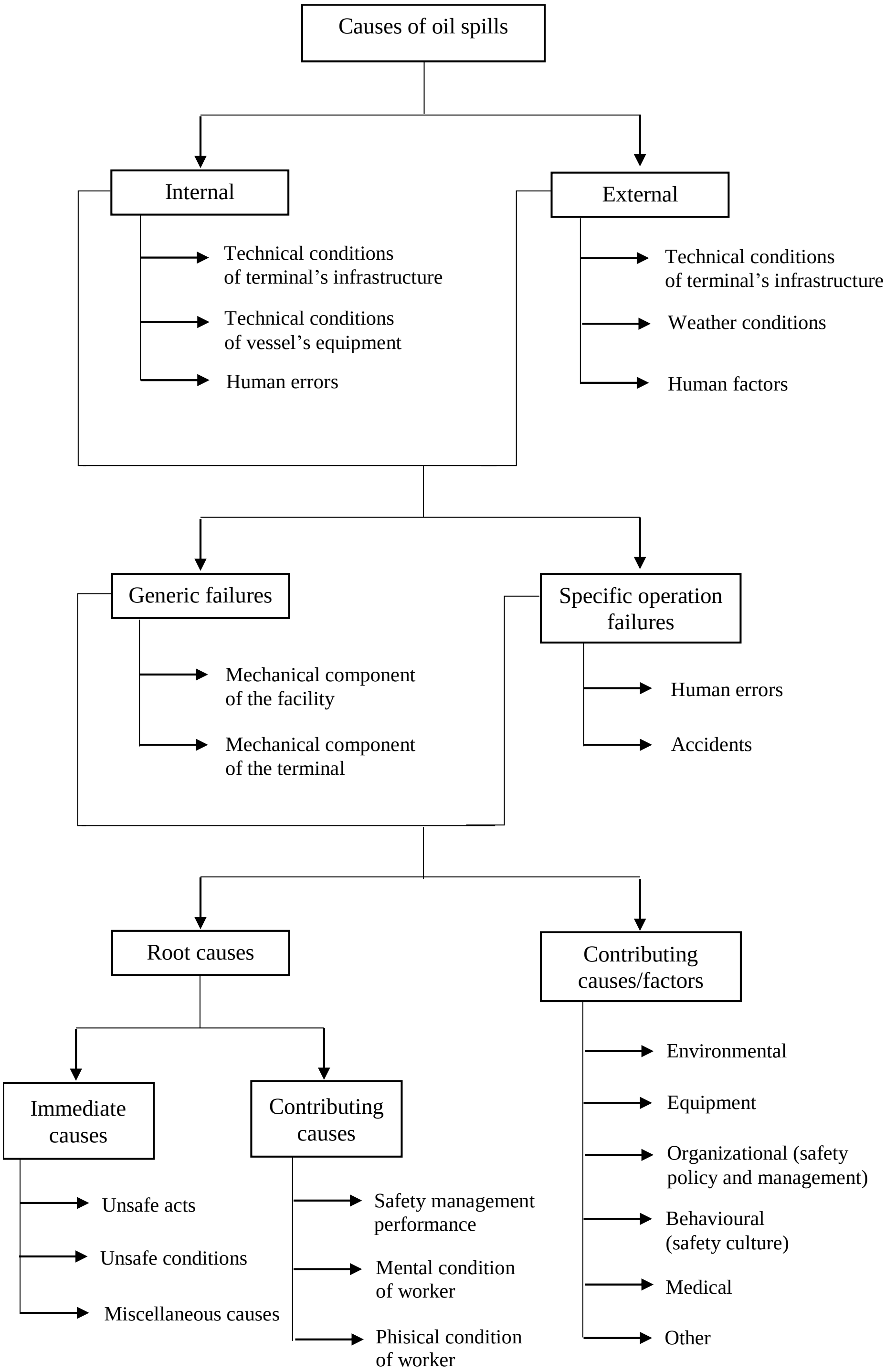

Figure 3. Types of oil spill causes.

Sometimes oil spills during the crude oil transfer can be caused by both human error and mechanical damage. Pressure upsurge inside the pipelines as a hydraulic hammer's consequence can be caused by:

- pump start-up – a starting pump can generate high pressures;
- pump power failure – it can cause a pressure upsurge on the suction side and a pressure down-surge on the discharge side;
- valve opening and closing – sudden valve closure changes the velocity quickly and results in a pressure surge.

The pressure surge resulting from a sudden valve opening is usually not as excessive. Closing a valve at the downstream end of a pipeline creates a pressure wave that the moves backwards to the reservoir; improper operation or incorrect design of surge protection devices [12].

Accidents may also occur during the crude oil transfer process due to following external causes:

- technical conditions of oil terminal's infrastructure, associated with abrupt temperature changeover within arrangement: pipeline-liquid-ambient, damage caused by other objects operating in the vicinity of pipelines (ashore/sea), damage to installation and technological appliances due to external forces,
- human factor including terrorism,
- weather condition such as thunderstorm, winds, waves, icing, very high or low temperatures.

Causes of oil spills can be also divided into two other categories. These are generic failures associated with mechanical component of the facility or terminal and specific operating failures prime cause of which is human error. Specific operating failures can include also accidents.

Causes of oil spills in investigation reports are often classified as root causes and contributing causes or factors. Contributing factors can be associated with environment, equipment, safety policy and management, work practice, supervision, training. Contributing factors can be also classified as behavioural, medical, task errors and other. Root causes can be also grouped to immediate causes (unsafe acts, unsafe conditions and miscellaneous causes) and contributing caused (safety management performance, mental and physical condition of worker) [27]. Scheme of different classifications of oil spill causes is presented in Fig. 3.

The effects of accidents, which occur at time of oil transfer, are divided in following categories:

- damage to oil terminal's infrastructure and/or ship,
- short or long-term breaks in the functioning of the oil terminal,
- endanger to human health and life,
- environmental pollution that is the most important and financially significant for the polluter.

5. The crude oil transfer process in port terminal – Analysis of the technical system

5.1. Reliability analysis of the system and its components

In a multistate approach to the system's reliability analysis [15], it is assumed that all the components and the system under consideration have the reliability state set $\{0,1,...,z\}$ $(z \geq 1)$, where state 0 is the worst and state z is the best. The state of the system and components degrades over time. We denote the system lifetime in the state subset $\{u,u+1,...,z\}$ $(u = 0,1,...,z)$ by $T(u)$ and its reliability function by

$$\boldsymbol{R}(t,\cdot) = [\boldsymbol{R}(t,0), \boldsymbol{R}(t,1), \ldots, \boldsymbol{R}(t,z)], \quad t \geq 0, \qquad (22)$$

where $\boldsymbol{R}(t,u) = P(T(u) > t)$ $(u = 0,1,...,z)$. Further, we replace $\boldsymbol{R}(t,0) = P(T(0) > t)$, existing in (22), by 1.

In the reliability analysis of the system of crude oil transfer in a port terminal the following components have been distinguished: pipelines, pumps, outer and inner loading arms, valves, pipeline welds. Further in the reliability analysis of this system, they are considered as basic components. It is assumed that reliability states of the system and its components are differently defined depending on the type of element and the specificity of its failure. Namely, there have been distinguished four reliability state for pipelines and pipeline weldments, three reliability state for outer and inner loading arms, two reliability states for pumps and valves, and finally three reliability state for the system of crude oil transfer. These reliability states are described below in details. On the basis of approximate mean values of the components' lifetimes in reliability states, obtained from experts exploiting the system, the failure rates of these components are estimated. The evaluated failure rates for two-state components and the intensities of leaving the reliability state subsets for multistate components, are used in further reliability analysis of the system as parameters of the components' exponential reliability functions.

During crude oil loading the cargo movement from storage tanks (oil reservoir on the wharf) through the pipeline system to tanks on a tanker takes place, during discharging the process is reversed. The scheme of crude oil transfer in the oil port terminal is given in Fig. 4. Processes related to crude oil transfer, i.e. oil loading, discharging and internal transfer are described in Section 2.1.

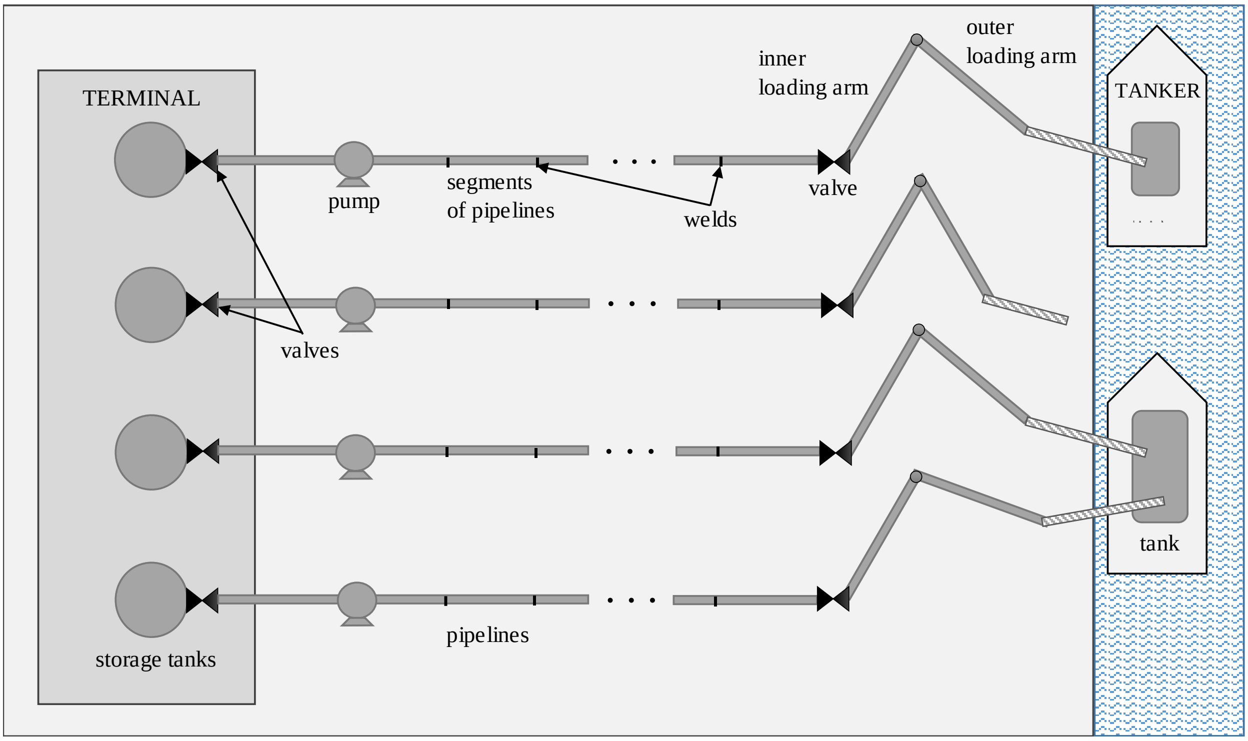

Figure 4. A scheme of crude oil transfer in the oil port terminal.

We assume that systems S, is composed of multistate components, with the reliability functions given below.

For a component E_1 i.e. a valve, two following reliability states are distinguished:

- state 1 – a valve is working properly without any defects,
- state 0 – a valve is failed,

and it has the reliability function

$$R_1(t,\cdot) = [1, R_1(t,1)], \quad t \ge 0, \tag{23}$$

with exponential coordinate

$$R_1(t,1) = \exp[-\lambda_1(1)t], \; t \ge 0. \tag{24}$$

The mean value of the valve lifetime in the reliability state {1}, based on expert opinion, is:

$$M_1(1) \cong 40 \text{ years}. \tag{25}$$

The failure rate of the component E_1 exponential reliability function (23)-(24), evaluated from (25), is

$$\lambda_1(1) = \frac{1}{M_1(1)} = 0.0250 \, [\text{years}^{-1}]. \tag{26}$$

For a component E_2 i.e. a pipeline or a pipe segment, four reliability states are distinguished:

- state 3 – a pipeline is new or after conservation with an anti-corrosion coating thickness of 100-330 μm (over 100 micrometres), pipeline without traces of corrosion,
- state 2 – a pipeline partially coated with the anti-corrosion coating (coating thickness less than 100 μm), corrosion losses of pipeline walls not exceeding 10% of the nominal wall thickness,
- state 1 – corrosion losses of pipeline walls not exceeding 30% of the nominal wall thickness,
- state 0 – corrosion losses of pipeline walls exceeding 30% of the nominal wall thickness, a pipeline is corroded and unusable.

Component E_2 has the exponential reliability function

$$R_2(t,\cdot) = [1, R_2(t,1), R_2(t,2), R_2(t,3)], \quad t \ge 0, \tag{27}$$

where

$$R_2(t,u) = \exp[-\lambda_2(u)t], \quad t \ge 0, \; u = 1,2,3. \tag{28}$$

The mean values of the pipeline lifetimes in the reliability state subsets {1,2,3}, {2,3}, {3}, estimated on the basis of the expert opinions, respectively are:

$$M_2(1) \cong 60, \;\; M_2(2) \cong 30, \;\; M_2(3) \cong 15 \text{ years}. \tag{29}$$

The rates of leaving the reliability state subsets {1,2,3}, {2,3}, {3}, of the component E_2 exponential reliability function (27)-(28), evaluated from (29), respectively are:

$$\lambda_2(1) = \frac{1}{M_2(1)} = 0.0167,\ \lambda_2(2) = \frac{1}{M_2(2)} = 0.0333,$$

$$\lambda_2(3) = \frac{1}{M_2(3)} = 0.0667\ [\text{years}^{-1}]. \qquad (30)$$

For a component E_3 i.e. a pump, two following reliability states are distinguished:

- state 1 – a pump is working properly without any defects,
- state 0 – a pump is failed,

and it has reliability function

$$R_3(t,\cdot) = [1, R_3(t,1)],\ \ t \ge 0, \qquad (31)$$

with exponential co-ordinate

$$R_3(t,1) = \exp[-\lambda_3(1)t],\ \ t \ge 0. \qquad (32)$$

The mean value of the pipeline lifetime in the reliability state {1}, based on expert opinion, is:

$$M_3(1) \cong 10 \ \text{years}. \qquad (33)$$

The failure rate of the component E_3 exponential reliability function (31)-(32), evaluated from (33), is

$$\lambda_3(1) = \frac{1}{M_3(1)} = 0.1000\ \ [\text{years}^{-1}]. \qquad (34)$$

For a component E_4 i.e. a pipeline or a pipe segment, four reliability states have been distinguished:

- state 3 – a pipeline is new or after conservation with an anti-corrosion coating thickness of 100-330 µm (over 100 micrometres), pipeline without traces of corrosion,
- state 2 – a pipeline partially coated with the anti-corrosion coating (coating thickness less than 100 µm), corrosion losses of pipeline walls not exceeding 10% of the nominal wall thickness,
- state 1 – corrosion losses of pipeline walls not exceeding 30% of the nominal wall thickness,
- state 0 – corrosion losses of pipeline walls exceeding 30% of the nominal wall thickness, a pipeline is corroded and unusable.

Component E_4 has exponential reliability function given by

$$R_4(t,\cdot) = [1, R_4(t,1), R_4(t,2), R_4(t,3)],\ \ t \ge 0, \qquad (35)$$

where

$$R_4(t,u) = \exp[-\lambda_4(u)t],\ t \ge 0,\ u = 1,2,3. \qquad (36)$$

The mean values of the component E_4 lifetimes in the reliability state subsets {1,2,3}, {2,3}, {3}, estimated on the basis of the expert opinions, respectively are:

$$M_4(1) \cong 60,\ \ M_4(2) \cong 30,\ \ M_4(3) \cong 15\ \ \text{years}. \qquad (37)$$

The rates of leaving the reliability state subsets {1,2,3}, {2,3}, {3}, of the component E_4 exponential reliability function (35)-(36), evaluated from (37), respectively are:

$$\lambda_4(1) = \frac{1}{M_4(1)} = 0.0167,\ \lambda_4(2) = \frac{1}{M_4(2)} = 0.0333,$$

$$\lambda_4(3) = \frac{1}{M_4(3)} = 0.0667\ [\text{years}^{-1}]. \qquad (38)$$

For a component E_5 i.e. a weld (weldments), four reliability states are distinguished:

- state 3 – a weld is new or after conservation, a leak test has been performed,
- state 2 – welded structures are changed however no leaks are detected, pitting corrosion in pipeline weld zones not exceeding 10% of the nominal wall thickness,
- state 1 – advanced corrosion in pipeline weld zones, however no leaks are detected,
- state 0 – detected failure of a weld, including corrosion failures, loss of leak tightness on the weld.

Component E_5 has exponential reliability function given by

$$R_5(t,\cdot) = [1, R_5(t,1), R_5(t,2), R_5(t,3)],\ \ t \ge 0, \qquad (39)$$

where

$$R_5(t,u) = \exp[-\lambda_5(u)t],\ t \ge 0,\ u = 1,2,3. \qquad (40)$$

The mean values of the component E_5 lifetimes in the reliability state subsets {1,2,3}, {2,3}, {3}, estimated on the basis of the expert opinions, respectively are:

$$M_4(1) \cong 15,\ \ M_4(2) \cong 10,\ \ M_4(3) \cong 5\ \ \text{years}. \qquad (41)$$

The rates of leaving the reliability state subsets {1,2,3}, {2,3}, {3}, of the component E_5 exponential reliability function (39)-(40), evaluated from (41), respectively are:

$$\lambda_5(1) = \frac{1}{M_5(1)} = 0.0667, \ \lambda_5(2) = \frac{1}{M_5(2)} = 0.1000,$$

$$\lambda_5(3) = \frac{1}{M_5(3)} = 0.2000 \ [\text{years}^{-1}]. \quad (42)$$

For a component E_6 i.e. a valve, two following reliability states are distinguished:

- state 1 – a valve is working properly without any defects,
- state 0 – a valve is failed/ is leaking,

and it has reliability function

$$R_6(t,\cdot) = [1, R_6(t,1)], \ t \geq 0, \quad (43)$$

with exponential co-ordinate

$$R_6(t,1) = \exp[-\lambda_6(1)t], \ t \geq 0. \quad (44)$$

The mean value of the component E_6 lifetime in the reliability state {1}, based on expert opinion, is:

$$M_6(1) \cong 15 \ \text{years}. \quad (45)$$

The failure rate of the component E_6 exponential reliability function (43)-(44), evaluated from (45), is

$$\lambda_6(1) = \frac{1}{M_6(1)} = 0.0667 \ [\text{years}^{-1}]. \quad (46)$$

For a component E_7 i.e. an inner or outer loading arm (outboard, inboard arms), three reliability states are distinguished:

- state 2 – a loading arm is new or after conservation, a leak test has been performed, loading arm has been inspected confirming its proper functioning, and that there are no leaks,
- state 1 – traces of fatigue in a loading arm material, corrosion of loading arm walls not exceeding 30% of the nominal wall thickness, loading arm has been inspected confirming its proper functioning, and that there are no leaks,
- state 0 – a loading arm is failed, loss of leak tightness of a loading arm.

Component E_7 has exponential reliability function given by

$$R_7(t,\cdot) = [1, R_7(t,1), R_7(t,2)], \ t \geq 0, \quad (47)$$

where

$$R_7(t,u) = \exp[-\lambda_7(u)t], \ t \geq 0, \ u = 1,2. \quad (48)$$

The mean values of the component E_7 lifetimes in the reliability state subsets {1,2}, {2}, estimated on the basis of the expert opinions, respectively are:

$$M_7(1) \cong 15, \ M_7(2) \cong 8 \ \text{years}. \quad (49)$$

The rates of leaving the reliability state subsets {1,2}, {2}, of the component E_7 exponential reliability function (47)-(48), evaluated from (49), respectively are:

$$\lambda_7(1) = \frac{1}{M_7(1)} = 0.0667,$$

$$\lambda_7(2) = \frac{1}{M_7(2)} = 0.1250 \ [\text{years}^{-1}]. \quad (50)$$

For a component E_8 i.e. a valve, two following reliability states are distinguished:

- state 1 – a valve is working properly without any defects,
- state 0 – a valve is failed,

and it has reliability function

$$R_8(t,\cdot) = [1, R_8(t,1)], \ t \geq 0, \quad (51)$$

with exponential co-ordinate

$$R_8(t,1) = \exp[-\lambda_8(1)t], \ t \geq 0. \quad (52)$$

The mean value of the valve lifetime in the reliability state {1}, based on expert opinion, is:

$$M_8(1) \cong 15 \ \text{years}. \quad (53)$$

The failure rate of the component E_8 exponential reliability function (51)-(52), evaluated from (53), is

$$\lambda_8(1) = \frac{1}{M_8(1)} = 0.0667 \ [\text{years}^{-1}]. \quad (54)$$

We distinguish following four reliability states of the crude oil transfer system, concerned with the states of its components:

- state 3 – the system is in very good condition and it has been inspected confirming its proper functioning, all its components are in the best reliability states,

- state 2 – the system is in good condition and is usable, the system has been inspected confirming its proper functioning, and that there are no leaks, (it means that situation in which the multistate components are in state 2 or in state better than 2, but not all i.e. the system is not in the state 3),
- state 1 – the system is in good condition and is usable, no significant traces of corrosion of system components, there are no leaks during oil transfer, (it includes situation in which at least one of the multistate components is in state 1),
- state 0 – the system is not usable if at least one of its components is failed and not serviceable i.e. the component is in the state 0, for example loss of leak tightness has been detected.

It is assumed that in all operational states the system reliability structure is the same and the parameters of the system components do not change.

Analyzing first the crude oil transfer system as a single pipeline system composed of the components E_1, E_2, E_3, E_4, E_5, E_6, E_7, E_8, described earlier in this Section, we conclude that all its components must be operational so that the system can transfer crude oil. Thereby, we analyse the oil transfer system, consisting of a single pipeline system, as a multistate series system. Next, assuming that its components have exponential reliability functions with the intensities of leaving the reliability state subsets (26), (30), (34), (38), (42), (46), (50), (54), the system reliability function is given by the vector

$$\boldsymbol{R}(t,\cdot) = [1, \boldsymbol{R}(t,1), \boldsymbol{R}(t,2), \boldsymbol{R}(t,3)], \quad t \ge 0, \qquad (55)$$

with the coordinates

$$\boldsymbol{R}(t,1) = \prod_{i=1}^{8} R_i(t,1) = \exp[-0.4252t], \quad t \ge 0, \qquad (56)$$

$$\boldsymbol{R}(t,2) = R_1(t,1)R_2(t,2)R_3(t,1)R_4(t,2)R_5(t,2)$$

$$\cdot R_6(t,1)R_7(t,2)R_8(t,1) = \exp[-0.5500t], \; t \ge 0, \qquad (57)$$

$$\boldsymbol{R}(t,3) = R_1(t,1)R_2(t,3)R_3(t,1)R_4(t,3)R_5(t,3)$$

$$\cdot R_6(t,1)R_7(t,2)R_8(t,1) = \exp[-0.7168t], \; t \ge 0. \qquad (58)$$

The reliability function coordinates of the crude oil transfer system, given by (56)-(58), are illustrated in Fig. 5.

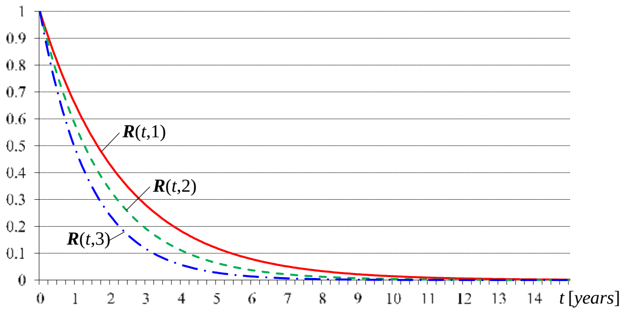

Figure 5. The graphs of the reliability function coordinates for crude oil transfer system.

The mean values and the standard deviations of the system lifetimes in the reliability state subsets {1,2,3}, {2,3}, {3}, calculated from (56)-(58) according to formulas given in [15], respectively are:

$$\mu(1) \cong 2.352 \text{ years}, \; \sigma(1) \cong 2.352 \text{ years}, \qquad (59)$$

$$\mu(2) \cong 1.818 \text{ years}, \; \sigma(2) \cong 1.818 \text{ years}, \qquad (60)$$

$$\mu(3) \cong 1.395 \text{ years}, \; \sigma(3) \cong 1.395 \text{ years}. \qquad (61)$$

The mean values of the system lifetimes in the particular states 1,2,3, by (59)-(61), in years are:

$$\bar{\mu}(1) = \mu(1) - \mu(2) \cong 0.534,$$

$$\bar{\mu}(2) = \mu(2) - \mu(3) \cong 0.423,$$

$$\bar{\mu}(3) = \mu(3) \cong 1.395. \qquad (62)$$

If $r = 2$ is the critical reliability state of crude oil transfer system, then from [15], the system risk function is given by

$$\boldsymbol{r}(t) = 1 - \boldsymbol{R}(t,2) = 1 - \exp[-0.55t], \quad t \ge 0.$$

Hence, the moment when the system risk function exceeds a permitted level, for instance $\delta = 0.1$, from [15], is

$$\tau = \boldsymbol{r}^{-1}(\delta) \cong 0.192 \text{ year} \cong 70 \text{ days}. \qquad (64)$$

For assumed permitted level $\delta = 0.2$, the moment of it exceeding by the system risk function is

$$\tau \cong 0.406 \text{ year} \cong 148 \text{ days}. \qquad (65)$$

The graph of the system risk function, called the fragility curve, is illustrated in Fig. 6.

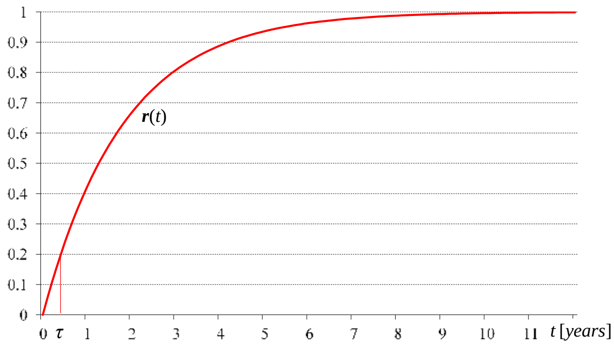

Figure 6. The graph of the crude oil transfer system risk function.

In the second case, we consider the crude oil transfer system consisting of four pipeline systems with identical series reliability structure and reliability function given by (55)-(58). We assume that these four pipeline systems are linked in parallel reliability structure. In that case, the reliability function of the crude oil transfer system is given by the vector [15]

$$\boldsymbol{R}_4(t,\cdot) = [1, \boldsymbol{R}_4(t,1), \boldsymbol{R}_4(t,2), \boldsymbol{R}_4(t,3)], \ \ t \geq 0, \quad (66)$$

with the coordinates

$$\boldsymbol{R}_4(t,u) = 1 - [1 - \boldsymbol{R}(t,u)]^4, \ \ t \geq 0, \ u = 1,2,3, \quad (67)$$

where $\boldsymbol{R}(t,u)$, $u = 1,2,3$, are the reliability function coordinates for the single pipeline system given by (56)-(58).
Using the results (56)-(58), we obtain the reliability function of the crude oil transfer system consisting of four pipeline systems in the form

$$\boldsymbol{R}_4(t,\cdot) = [1, \boldsymbol{R}_4(t,1), \boldsymbol{R}_4(t,2), \boldsymbol{R}_4(t,3)], \ \ t \geq 0, \quad (68)$$

where

$$\boldsymbol{R}_4(t,1) = 4\exp[-1.2756t] - \exp[-1.7008t]$$

$$-6\exp[-0.8504t] + 4\exp[-0.4252t], \ t \geq 0, \quad (69)$$

$$\boldsymbol{R}_4(t,2) = 4\exp[-1.65t] - \exp[-2.2t]$$

$$-6\exp[-1.1t] + 4\exp[-0.55t], \ t \geq 0, \quad (70)$$

$$\boldsymbol{R}_4(t,3) = 4\exp[-2.1504t] - \exp[-2.8672t]$$

$$-6\exp[-1.4336t] + 4\exp[-0.7168t], \ t \geq 0. \quad (71)$$

The mean values and the standard deviations of the system lifetimes in the reliability state subsets {1,2,3}, {2,3}, {3}, using (69)-(71) and from [15], respectively are:

$$\mu_4(1) \cong 4.900 \text{ years}, \ \sigma_4(1) \cong 2.806 \text{ years}, \quad (72)$$

$$\mu_4(2) \cong 3.788 \text{ years}, \ \sigma_4(2) \cong 2.169 \text{ years}, \quad (73)$$

$$\mu_4(3) \cong 2.906 \text{ years}, \ \sigma_4(3) \cong 1.665 \text{ years}. \quad (74)$$

The mean values of the system lifetimes in the particular states 1,2,3, by (72)-(74), in years are:

$$\bar{\mu}_4(1) = \mu_4(1) - \mu_4(2) \cong 1.112,$$

$$\bar{\mu}_4(2) = \mu_4(2) - \mu_4(3) \cong 0.882,$$

$$\bar{\mu}_4(3) = \mu_4(3) \cong 2.906. \quad (75)$$

If r = 2 is the critical reliability state of the crude oil transfer system consisting of four pipeline systems, then from [15] its risk function is given by

$$\boldsymbol{r}_4(t) = 1 - \boldsymbol{R}_4(t,2) = 1 - 4\exp[-1.65t] + \exp[-2.2t]$$

$$+6\exp[-1.1t] - 4\exp[-0.55t], \ t \geq 0.$$

Hence, the moment when the system risk function exceeds a permitted level, for instance δ = 0.1, from [15], is

$$\tau_4 = \boldsymbol{r}_4^{-1}(\delta) \cong 1.503 \text{ years} \cong 1 \text{ year } 184 \text{ days}. \quad (77)$$

For assumed permitted level δ = 0.2, the moment of it exceeding risk function by the crude oil transfer system consisting of four pipeline systems, is

$$\tau_4 \cong 2.009 \text{ years} \cong 2 \text{ years } 3 \text{ days}. \quad (78)$$

5.2. Availability analysis of the system and its components

In this section, we assume that the crude oil transfer system is repaired after exceeding its critical reliability state r = 2. The system components, by the assumption, have exponential reliability functions with the intensities of leaving the reliability state subsets given by (26), (30), (34), (38), (42), (46), (50) and (54). Under these assumptions, the availability analysis of the crude oil transfer system as repairable system with negligible renewal time and in case when renewal time is not negligible, is performed and basic availability characteristics are determined in this paper. Namely, for a repairable system with negligible renovation time the expected value and the variance of the time until the successive exceeding the reliability critical state by the system, and the expected value and the variance of the number of times that the reliability critical state is exceeded until the fixed moment are given. In case of a repairable system with non-negligible renovation time, the expected value and variance of time until the successive exceeding the reliability critical state by the system, the expected value and variance of the number of times the system exceeds the reliability critical state until the fixed time point, the expected value and variance of time until the successive system renewals, the expected value and variance of the number of system renewals until the fixed moment and the availability coefficient of the system at the fixed time point are determined.

We denote by $T(r)$ the system's lifetime in the reliability state subset $\{r, r+1, \ldots, z\}$. By the renewal of the system, we mean the operation that causes the system to return to the best reliability state z. Thus, the time until the critical state r is next exceeded has the same $T(r)$ distribution. Further, we define a random variable $T^{(N)}(r)$, $r = 1,2,...,z$ and $N = 1,2,\ldots$, describing the time between the moment of the N-1 system renovation and the *Nth* time that the system critical state is exceeded, wherein $T^{(1)}(r)$ denotes the time between the commencement of the system operation and the moment of its first renovation. We assume that the random variables $T^{(1)}(r), T^{(2)}(r), \ldots$, $r = 1,2,...,z$, are independent and have identical $T(r)$ distributions with expected value $\mu(r)$ and standard deviation $\sigma(r) \neq 0$.

In the first case, it is assumed that the time of system's renovation is very small, comparing to its lifetimes in the reliability state subsets not worse than the critical reliability state, we may omit it.

Under these assumptions, the variable $S^{(N)}(r)$ representing the time until the *Nth* time the system exceeds the reliability critical state r, has, for sufficiently large N, an approximately normal distribution with the expected value and the variance [16], respectively, given by

$$E[S^{(N)}(r)] \cong N\mu(r),$$

$$D[S^{(N)}(r)] \cong N\sigma^2(r), \ r \in \{1,2,...,z\}. \qquad (79)$$

Assuming as before that the critical reliability state of crude oil transfer system is $r = 2$, in case of the transfer system composed of a single pipeline system, substituting in (79) the expected value $\mu(2)$ and standard deviation $\sigma(2)$ of the system lifetime in the reliability state subset $\{1,2,3\}$, given by (60), we get

$$E[S^{(N)}(2)] \cong 1.818N \ \text{years},$$

$$D[S^{(N)}(2)] \cong 3.305N \ \text{years}. \qquad (80)$$

For the crude oil transfer system consisting of four pipeline systems these availability characteristics, applying (79) and using (73), are

$$E[S_4^{(N)}(2)] \cong 3.788N \ \text{years},$$

$$D[S_4^{(N)}(2)] \cong 4.705N \ \text{years}. \qquad (81)$$

Next, we denote by $N(t,r)$ the number of systems exceeding the critical state r, i.e., the number of renewals of the system, up to the time point t.

Using the results given in [16], the number $N(t,r)$ of times the system exceeds the reliability critical state r up to the time point $t, t \geq 0$, has, for sufficiently large t, an approximately normal distribution with the expected value and the variance, respectively, given by

$$E[N(t,r)] \cong \frac{t}{\mu(r)},$$

$$D[N(t,r)] \cong \frac{t}{\mu^3(r)}\sigma^2(r), \ r \in \{1,2,...,z\}. \qquad (82)$$

Similarly, in case of the transfer system composed of a single pipeline system, substituting in (82) the expected value and standard deviation of the system lifetime in the reliability state subset $\{1,2,3\}$, given by (60), we have

$$E[N(t,2)] \cong 0.55t, \ \ D[N(t,2)] \cong 0.55t, \qquad (83)$$

and in case of the crude oil transfer system consisting of four pipeline systems, substituting in (82) the expected value and standard deviation given by (73), we obtain

$$E[N_4(t,2)] \cong 0.264t, \ \ D[N_4(t,2)] \cong 0.087t. \qquad (84)$$

In the second case, we consider the system of crude oil transfer as a repairable system with not negligible time, assuming that the time of system's renovation cannot be omitted. The critical reliability state of the system is $r = 2$. In that case, under assumption that the successive times of system's renovations are independent and have an identical distribution function with the expected value and standard deviation

$$\mu_0(r) = 0.08 \text{ year}, \ \sigma_0(r) = 0.08 \text{ year}, \quad (85)$$

we get following results.
The expected value and the variance of time $\bar{S}^{(N)}(r)$ until the *Nth* exceeding the reliability critical state *r* by the system, for sufficiently large *N*, from [16], are respectively given by

$$E[\bar{S}^{(N)}(r)] \cong N\mu(r) + (N-1)\mu_0(r),$$

$$D[\bar{S}^{(N)}(r)] \cong N\sigma^2(r) + (N-1)\sigma_0^2(r), \ r \in \{1,2,...,z\}. \quad (86)$$

Further substituting (60) and (85) into (86) for the crude oil transfer system composed of a single pipeline system with the critical state *r* = 2, we get

$$E[\bar{S}^{(N)}(2)] \cong 1.898N - 0.08 \text{ years},$$

$$D[\bar{S}^{(N)}(2)] \cong 3.312N - 0.006 \text{ years}, \quad (87)$$

and in case of the crude oil transfer system consisting of four pipeline systems, assuming that the critical state is *r* = 2 and the successive times of system's renovations are independent and have an identical distribution function with the expected value and standard deviation given by (85), using the results (73), we obtain

$$E[\bar{S}_4^{(N)}(2)] \cong 3.868N - 0.08 \text{ years},$$

$$D[\bar{S}_4^{(N)}(2)] \cong 4.711N - 0.006 \text{ years}. \quad (88)$$

The expected value and variance of the number $\bar{N}(t,r)$ of times the system exceeds the reliability critical state *r* up to the time point $t, t \ge 0$, for sufficiently large *t*, from [16], are respectively given by

$$E[\bar{N}(t,r)] \cong \frac{t + \mu_0(r)}{\mu(r) + \mu_0(r)},$$

$$D[\bar{N}(t,r)] \cong \frac{t + \mu_0(r)}{(\mu(r) + \mu_0(r))^3}(\sigma^2(r) + \sigma_0^2(r)),$$
$$r \in \{1,2,...,z\}. \quad (89)$$

And for the critical state *r* = 2, applying (89) and using (60), (85), in case of the crude oil transfer system composed of a single pipeline system we get

$$E[\bar{N}(t,2)] \cong 0.527t + 0.042,$$

$$D[\bar{N}(t,2)] \cong 0.484t + 0.039, \ t \ge 0. \quad (90)$$

In case of the crude oil transfer system consisting of four pipeline systems, by (89) and using (73), (85), these availability characteristics take form

$$E[\bar{N}_4(t,2)] \cong 0.259t + 0.021,$$

$$D[\bar{N}_4(t,2)] \cong 0.081t + 0.007, \ t \ge 0. \quad (91)$$

The expected value and variance of time $\bar{\bar{S}}^{(N)}(r)$ until the *Nth* system's renovation, for sufficiently large *N*, from [16], are respectively given by

$$E[\bar{\bar{S}}^{(N)}(r)] \cong N(\mu(r) + \mu_0(r)),$$

$$D[\bar{\bar{S}}^{(N)}(r)] \cong N(\sigma^2(r) + \sigma_0^2(r)), \ r \in \{1,2,...,z\}. \quad (92)$$

Next, for the single pipeline crude oil transfer system, substituting in (92) values given in (60) and (85), we get

$$E[\bar{\bar{S}}^{(N)}(2)] \cong 1.898N \text{ years},$$

$$D[\bar{\bar{S}}^{(N)}(2)] \cong 3.312N \text{ years}. \quad (93)$$

In case of the crude oil transfer system consisting of four pipeline systems, substituting in (92) values given in (73) and (85), we obtain

$$E[\bar{\bar{S}}_4^{(N)}(2)] \cong 3.868N \text{ years},$$

$$D[\bar{\bar{S}}_4^{(N)}(2)] \cong 4.711N \text{ years}. \quad (94)$$

The expected value and variance of the number $\bar{\bar{N}}(t,r)$ of system's renovation up to the time point $t, t \ge 0$, for sufficiently large *t*, from [16], are respectively given by

$$E[\bar{\bar{N}}(t,r)] \cong \frac{t}{\mu(r) + \mu_0(r)},$$

$$D[\bar{\bar{N}}(t,r)] \cong \frac{t}{(\mu(r) + \mu_0(r))^3}(\sigma^2(r) + \sigma_0^2(r)),$$
$$r \in \{1,2,...,z\}. \quad (95)$$

For the single pipeline crude oil transfer system, substituting in (95) values given in (60) and (85), we get

$$E[\bar{\bar{N}}(t,2)] \cong 0.527t,\; D[\bar{\bar{N}}(t,2)] \cong 0.484t,\; t \geq 0. \quad (96)$$

Similarly, for the crude oil transfer system consisting of four pipeline systems, applying (95) and using (73), (85), we obtain

$$E[\bar{\bar{N}}_4(t,2)] \cong 0.259t,\; D[\bar{\bar{N}}_4(t,2)] \cong 0.081t,\; t \geq 0. \quad (97)$$

The steady availability coefficient of the system at the moment t, $t \geq 0$, for sufficiently large t, using results given in [16], is determined from the formula

$$A(t,r) \cong \frac{\mu(r)}{\mu(r) + \mu_0(r)},\; t \geq 0,\; r \in \{1,2,...,z\}, \quad (98)$$

and substituting (60) and (85) for the single pipeline transfer system with the critical state $r = 2$, this availability coefficient takes value

$$A(t,2) \cong 0.958,\;\; t \geq 0. \quad (99)$$

The steady availability coefficient of the system at the moment t, $t \geq 0$, for the crude oil transfer system consisting of four pipeline systems, applying (98) and using (73), (85), is

$$A_4(t,2) \cong 0.979,\;\; t \geq 0. \quad (100)$$

Finally, the steady availability coefficient in the time interval $< t; t+\tau)$, $\tau > 0$, of the crude oil transfer system composed of a single pipeline system, for sufficiently large t, from [16] is given by

$$A(t,\tau,r) \cong \frac{1}{\mu(r) + \mu_0(r)} \int_\tau^\infty \boldsymbol{R}(t,\, r)dt,$$

$$t \geq 0,\; \tau > 0,\; r \in \{1,2,...,z\}, \quad (101)$$

where for the critical state $r = 2$, the coordinate of the system reliability function $\boldsymbol{R}(t,2)$ is given by (57), $\mu(2)$ is given by (60) and the expected value of renovation time $\mu_0(2)$ by (85).
Thereby, the steady availability coefficient in the time interval given by (101), takes form

$$A(t,\tau,2) \cong 0.527 \int_\tau^\infty \exp[-0.55t]dt$$

$$\cong 0.958 \exp[-0.55\tau],\;\; t \geq 0,\; \tau > 0. \quad (102)$$

For example, for a period of one month, i.e. $\tau = 0.083$ year, the steady availability coefficient of this system in the time interval is 91.5%.
Similarly, the steady availability coefficient in the time interval $< t; t+\tau)$, $\tau > 0$, of the crude oil transfer system composed of four pipeline systems, for sufficiently large t, from [16] is given by

$$A_4(t,\tau,r) \cong \frac{1}{\mu_4(r) + \mu_0(r)} \int_\tau^\infty \boldsymbol{R}_4(t,\, r)dt,$$

$$t \geq 0,\; \tau > 0,\; r \in \{1,2,...,z\}, \quad (103)$$

where for the critical state $r = 2$, the coordinate of the system reliability function $\boldsymbol{R}_4(t,2)$ is given by (70), $\mu_4(2)$ is given by (73) and the expected value of renovation time $\mu_0(2)$ by (85).
Thereby, the steady availability coefficient in the time interval, for that transfer system, by (103), is given by

$$A_4(t,\tau,2) \cong 0.259 \int_\tau^\infty 4\exp[-1.65t] - \exp[-2.2t]$$

$$-6\exp[-1.1t] + 4\exp[-0.55t]dt$$

$$\cong 0.6279 \exp[-1.65\tau] - 0.1177 \exp[-2.2\tau]$$

$$-1.4127 \exp[-1.1\tau] + 1.8836 \exp[-0.55\tau],$$

$$t \geq 0,\; \tau > 0. \quad (104)$$

For example, for a period of one month, i.e. $\tau = 0.083$ year, the steady availability coefficient of this system in the time interval is 95.6%.
The steady availability coefficients of the system, given by (98) and (101), determines the probability of the system being in the ability state respectively at the moment and in the time interval.

6. The crude oil transfer process in port terminal – Analysis including the human factor

6.1. Fault Tree Analysis

Similarly, as in [10], we propose Fault Tree Analysis (FTA) to identify and analyse potential causes and possible scenarios of oil spill incidents and accidents in the oil port terminal during oil transfer. The identification of threats together with the preparation of a comprehensive list of all possible threats is an essential and crucial step in the analysis and improvement of port safety [25]. The phase of hazard identification can take into account root causes and contributing factors that are listed and classified in next section. The identification of potential threats and analysis of the course of events can help in avoiding oil leakages and spills, and mitigating consequences if they occur. Fig. 7 presents the fault tree for oil spill scenario in a port oil terminal.

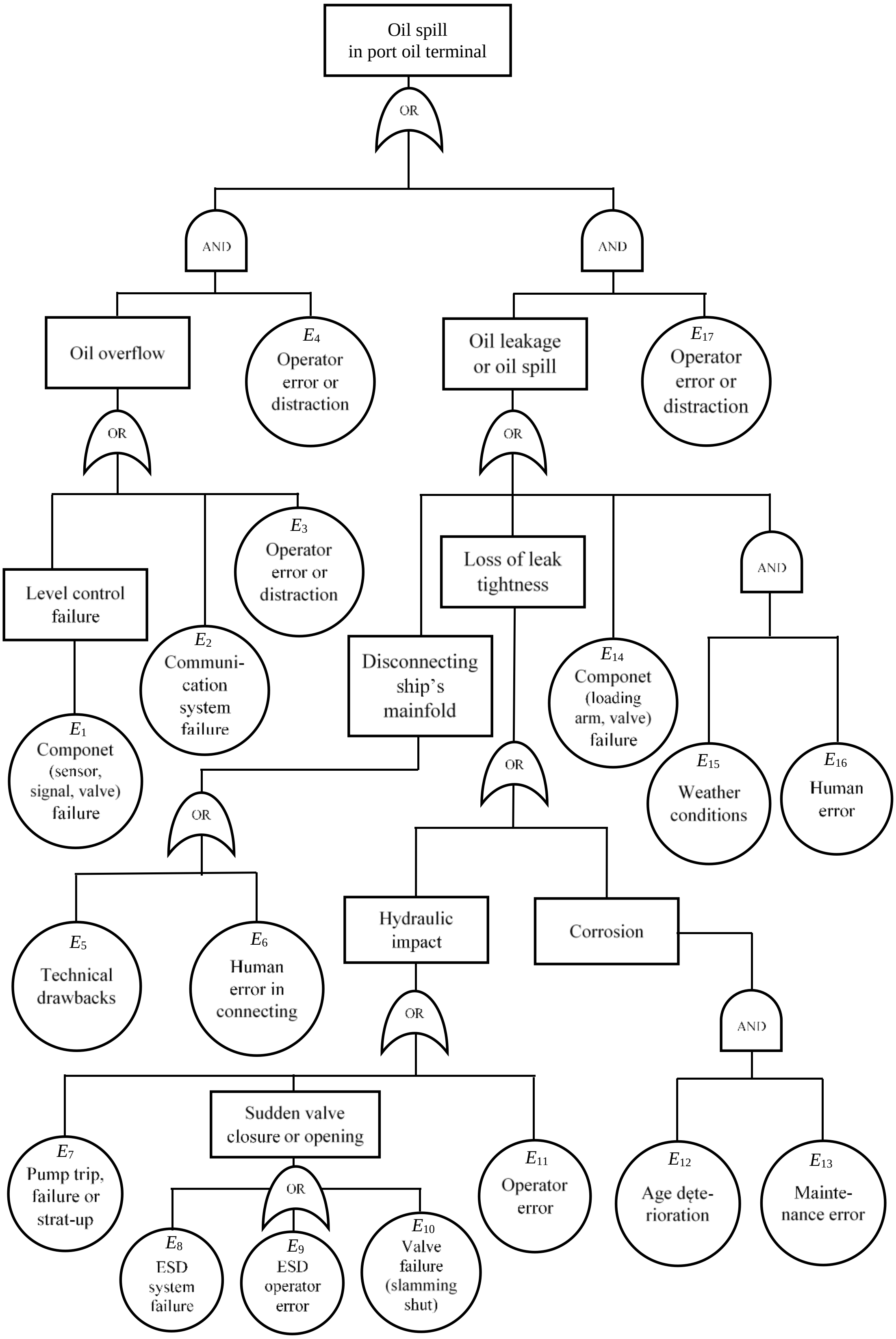

Figure 7. Fault tree for oil spill in port oil terminal.

Further, using fault tree the probability of oil spill in oil port terminal is estimated, [1], [3], [7], [17]:

$$P(E_{oil\_spill}) = (P(E_1) + P(E_2) + P(E_3)) \cdot P(E_4)$$

$$+(\sum_{i=5}^{11} P(E_i) + P(E_{12}) \cdot P(E_{13})) \cdot P(E_{17})$$

$$+(P(E_{14}) + P(E_{15}) \cdot P(E_{16})) \cdot P(E_{17}), \qquad (105)$$

where $P(E_i)$ denotes the occurrence probability of a basic event E_i, $i = 1,2,\ldots,17$.

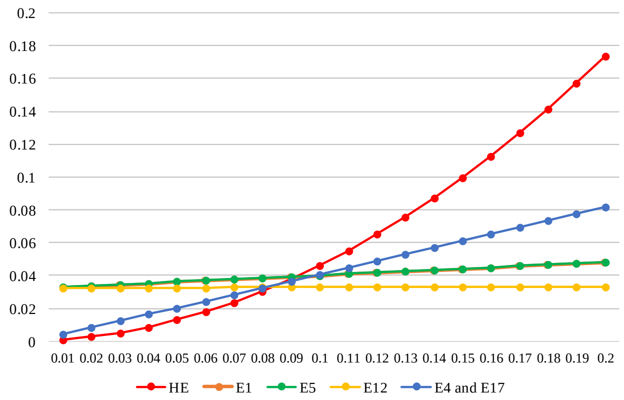

Figure 8. Sensitivity analysis for oil spill in port oil terminal [year^{-1}].

A sensitivity analysis for exemplary data has been performed for the oil spill event in terms of all human errors during crude oil transfer (HE), operator error or distraction during oil overflow (event E_4) and during oil leakage (E_{17}), (Fig. 8). The effect of some basic events related to technical condition of infrastructure or equipment has been also analysed. Namely, component failure (E_1), technical drawbacks during disconnecting ship's manifold (E_5) and age deterioration causing corrosion (E_{12}). Further sensitivity analysis will allow indicating the most crucial factors in possible scenarios of oil spill.

From the analysis of critical fault routes at the FTA diagram, it can be noticed that human factor is very important during crude oil transfer process in the port terminal. Fuentes-Bargues et al. drew a similar conclusion in [10], where the results of sensitivity analysis, using FTA, stressed the significance of human behaviour in the scenario of a potential leak or a fuel spill. According to Chang and Lin [6] overfilling is the most frequent operational error. Operational error can cause overpressure in a pipeline, resulting in oil spill.

6.2. Human factors analysis and classification

Through the analysis of how accidents are caused, i.e. how oil leakage, oil overflow or oil spill have occurred, and the reverse direction analysis of possible event scenarios and potential causes of oil spill in port oil terminal, we identify threats, including human factor, that contributed to the oil spill incident. On the basis of such model, shown in Fig. 9, the Human Factor Investigation Tool (HFIT) is based [9]. This model assumes that in the chain of events the final direct cause of the accident is an action error.

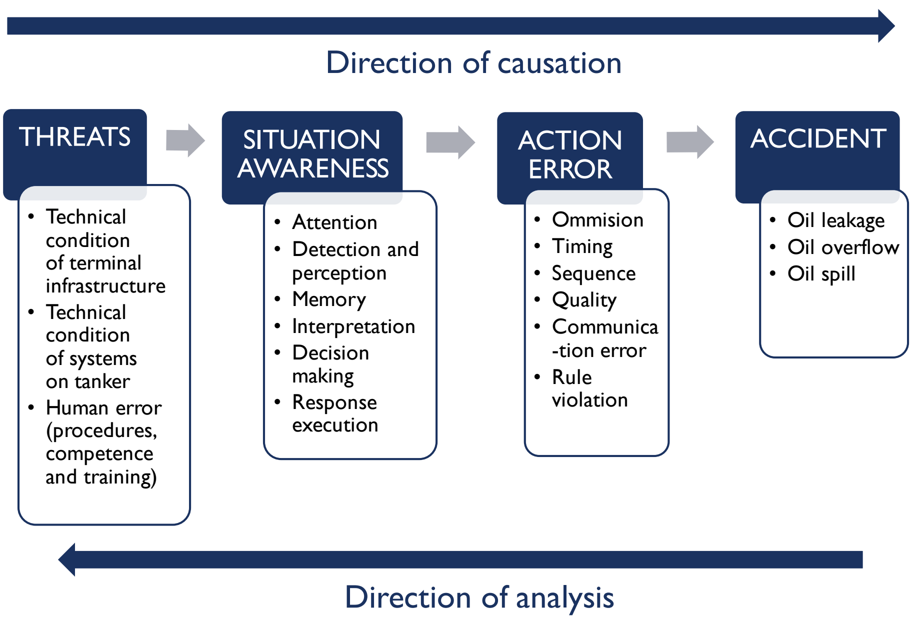

Figure 9. Diagram of the direction of causation analysis and the direction of the analysis identifying threats.

A similar conclusion was drawn from FTA analysis, where human factor is cause of the oil spill accident at least as a contributing factor. For example, operator error or distraction can often cause problems that consequently can lead to oil spill in the port terminal. Moreover, human factor as a multi-dimensional problem should be taken into account at various levels i.e. organization and management, behaviour and safety culture, including maintenance, physical and mental condition of worker/operator, and others (Fig. 10).

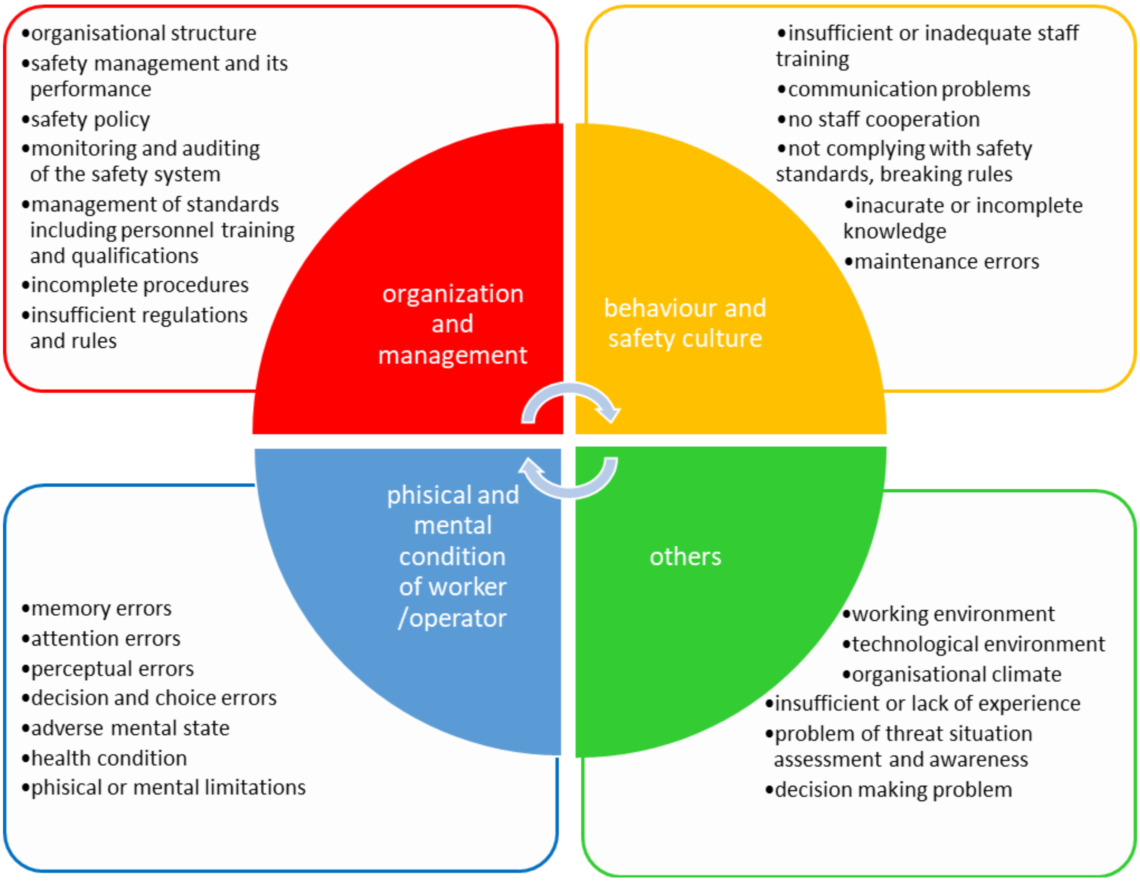

Figure 10. Human factors analysis and classification.

Factors affecting the safety of oil transfer in a terminal, even at particular level of analysis, are interrelated and influence each other [19]-[21]. Authors in [19] proposed Port Risk Management methodology to conduct risk evaluation of port container terminals. Without defined rules and procedures for dealing with specific situations and clearly defining responsibilities of workers at organization and management level, safety culture and behavior cannot be expected. Similarly, the problem of assessing the situation, awareness of threats and making decisions may result from the lack of adequate training and qualifications of the worker. At this point, it should be mentioned that education and training of emergency procedures and the estimation of system safety may also be of special importance. A very important factor is proper communication between the operators and knowledge of the relevant terminology. The necessary element eliminating the human error largely is the safety and security control and supervision system. Detailed analysis may indicate the weakest point in the process of oil transfer and help to find the most effective solutions.

Analysis of human errors, both direct and indirect, can apply to prioritize the preventive actions, management, regulations and rules to avoid oil spill incidents and accidents in port terminal and to minimize the probability of their occur.

7. Prevention of oil spill during crude oil transfer in port terminal

To prevent oil spill during crude oil transfer in a terminal, technical solutions, presented in Sections 7.1 and 7.2, and solutions related to human factor, described in Section 7.3 (Fig. 11) are considered in this paper. Technical solutions include the use of Emergency Shut Down (ESD) System and associated safety systems, such as the Emergency Release

System (ERS) and other surge relief systems. One of the problems is the lack of uniform requirements, for example related to linked ESD systems, which could be the standard for both terminals and crude oil tankers. In the second group of solutions, we present safety procedures during liquid cargo transfer and trainings, including courses on the Liquid Cargo Handling Simulator (LCHS).

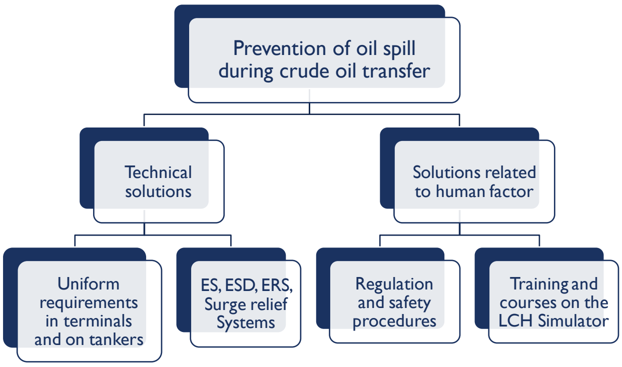

Figure 11. Diagram of solutions to prevent oil spill during crude oil transfer.

Analysing the safety of the crude oil transfer process in the terminal, it can be noticed that the human factor is crucial. For example, the statistical analysis of the system operation process shows that the period in which the oil may be spilled due to tank overflows, compared to the period in which cargo is loaded/unloaded with full rate and there is a threat of sudden oil spill is significantly shorter. However, in practice, accidents related to oil leakage or oil spill in the final stage of cargo transfer occur most often in terminals due to the important role of the operator (both on a tanker and in a terminal). Therefore, accurate and strict following the procedures and safety rules during crude oil transfer and the ability to respond quickly and appropriately in emergency situations can significantly increase the safety of the oil transfer process in a terminal.

7.1. Technical solutions used in oil terminals

Critical infrastructure monitoring and protection systems, such as pipeline systems, transshipment berths, transfer's area with pumping devices, have been used for many years in terminals used for LNG and LPG gas transfer. Applied standards and solutions in LNG terminals and on LNG carriers were developed by SIGTTO and implemented even during ordinary bunkering operations with LNG-powered vessels [22].
In many oil and fuel terminals in Europe, following the solutions and experience related to LNG transfer, actions are also taken to protect the oil terminal infrastructure. However, there are still no uniform requirements that could be the standard used both in terminals and crude oil tankers. Lack of the regulations and appropriate standards in this area means that despite there are many solutions in the design of ESD systems, in practice on tankers the existing standards of these systems are primarily associated with solutions used by producers of pumps and cargo systems.
In many oil terminals simple solutions based on ES (Emergency Stop) or ESD (Emergency Shut Down) systems are found, but due to the lack of specific standards, these are solutions that allow only partial control over transfer operations – usually, only in emergency situations.
Tankers' emergency stopping of unloading operations, is based on the ES system, which allows stopping of cargo pumps and reduction of pressure in the pipelines during unloading cargo to the oil terminal. In this situation, the signal for emergency stop operation is forced by pressing a button located near the cargo manifold or in the CCR (Cargo Control Room). Similar solutions, allowing emergency stop of transfer cargo near loading arms, also exist in oil terminals.

Figure 12. ES (Emergency Stop) button.

However, in all these cases, to activate both systems, there is a need for the presence of the ship's crew and / or personnel from terminal in the vicinity of the ES button and reliable communication between them so that the system is effective in emergency situations.
A much more effective solution compared to the use of the ES system is the use of the ESD system, allowing to stop cargo pumps in the terminal. This system allows the activation of a signal that stops the work of cargo pumps in the oil terminal, in emergency situations or in the absence of communication from the terminal personnel during the operations of melting ship tanks.

7.1.1. Emergency Shut Down (ESD) System

ESD systems for cargo transfers are used to stop the flow of cargo liquid and vapour in an emergency and to bring the cargo handling system to a safe, static condition. It is recommended that linked ESD systems are installed so that an ESD trip activated on the ship will send an ESD signal to the terminal and vice versa. A core recommendation of this paper is that, as a minimum, ESD is manually activated.

Some ship and terminal systems will include the provision for automatic shutdown of cargo transfers in abnormal operating conditions:

- high tank levels,
- high or low tank pressures,
- excessive pressure in the cargo transfer system,
- fire,
- gas detection,
- excessive ship movement or break-out.

Figure 13 presents screenshot of the LCH Simulator with the cargo tanks arrangement.

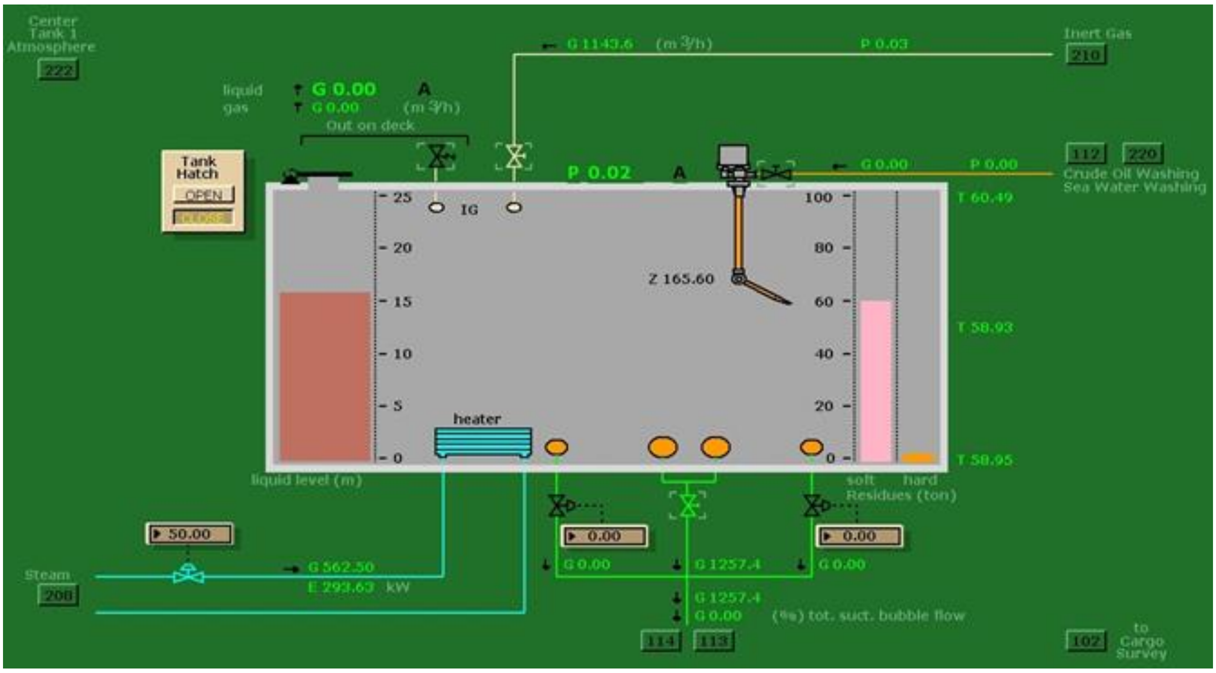

Figure 13. Crude oil tanker's cargo tank arrangements [26].

Figure 14 presents IGS (Inert Gas System) distribution during loading operation. Screenshot together with white arrows present main parts of IG system on deck tankers.

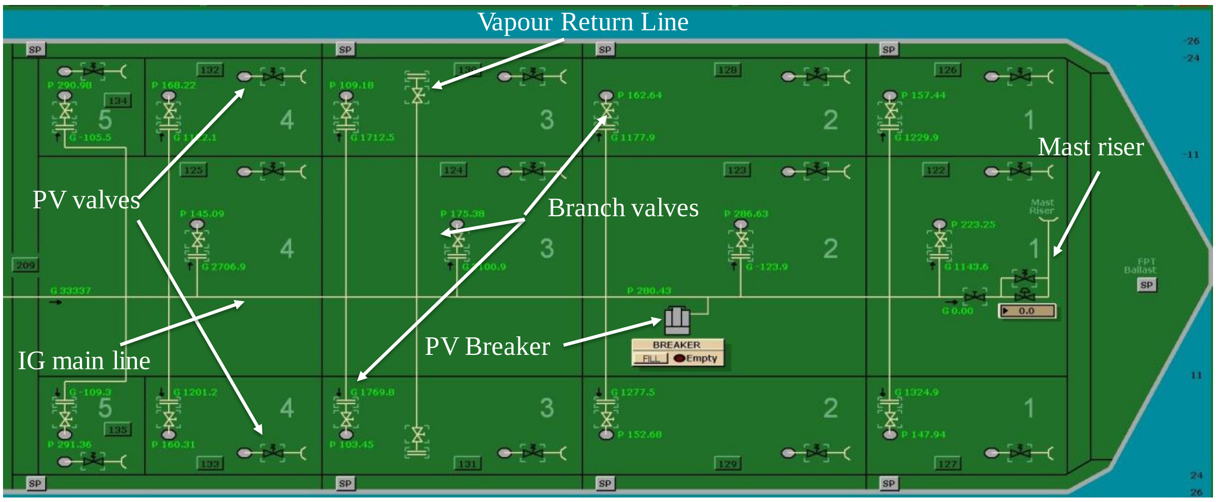

Figure 14. Inert Gas distribution systems [26].

IGS is using during loading operation to remove VOC from cargo tanks to the terminal VRU (Vapour Recovery Unit) through the Vapour Return Line. IGS using during unloading cargo fulfil upper parts of cargo tanks by inert gas to maintain positive pressure during whole operation.

Figure 15 presents IGP (Inert Gas Plant) arrangement in tanker's engine room. There are some limits of main parameters presented on Fig. 15 as pressure, oxygen and C_xH_y contents. In IGP some of equipment are duplicated as fans, water pumps to increase reliability of IG system.

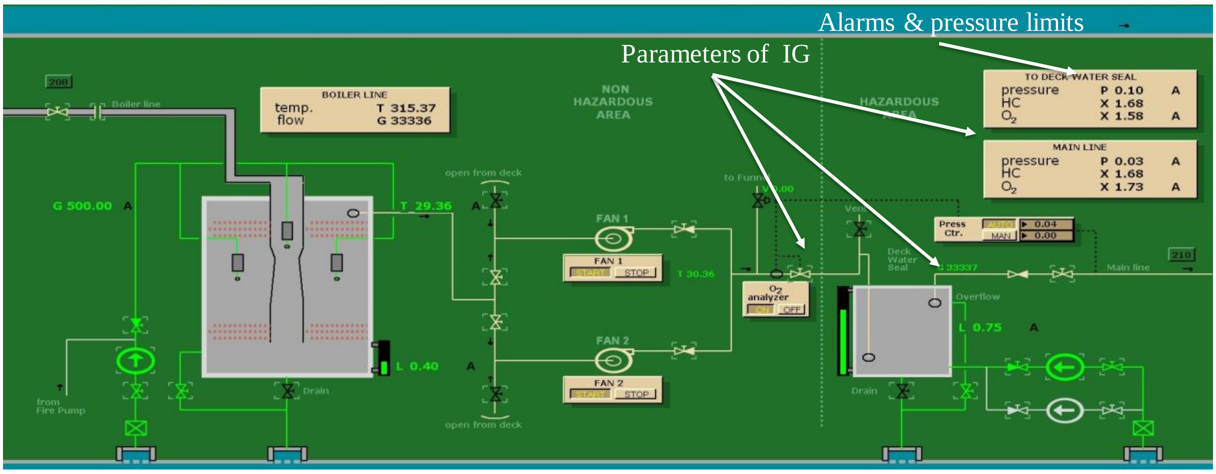

Figure 15. IGP Inert Gas Plant delivering IG to the main line on deck [26].

In a linked ESD system, the party receiving cargo, i.e. the ship in the loading port and the terminal in the discharge port, can stop cargo flow by shutting down the transfer pumps in a controlled way.
The receiving party should never have to shut valves against a full flow of incoming liquid.
A linked system also allows either party to activate a controlled shutdown of the transfer process if a leakage or fire is discovered, without generating unacceptable surge pressures in the pipework that would make the situation worse. Once the ESD has been activated, further action may need to be taken to secure ship and terminal systems.
Now, we describe emergency operation of normally linked systems. Linked ship and terminal ESD systems reduce the risk of hose or pipeline failure causing cargo spills in two ways. Excessive pressure surges caused by a unilateral shutdown can cause hose rupture and mechanical damage to valves, pipelines and supporting structures. Excessive vessel movement alongside the berth or vessel breakout from the berth may result in hose or MLA failure. The linked system should therefore be considered a critical safety system for cargo transfer operations. Pre-arrival testing of the linked ESD system will reduce the risk of a failure during operation, but contingency plans should be made for any failure of the linked system. It is recommended that the terminal and ship discuss contingency plans before operations begin. The terminal's emergency response procedures should also address failure of the linked system.
A pendant ESD unit may be used as a mitigation measure, if available.
Figure 16 presents example of Oil Terminal interface together with main elements as centrifugal cargo pumps with non-return valves, which protected cargo pumps or avoid backing flow of cargo from shore cargo tanks. There are some parameters of transfer as pressure and rate of transfer, display on each line in the vicinity of cargo pumps.

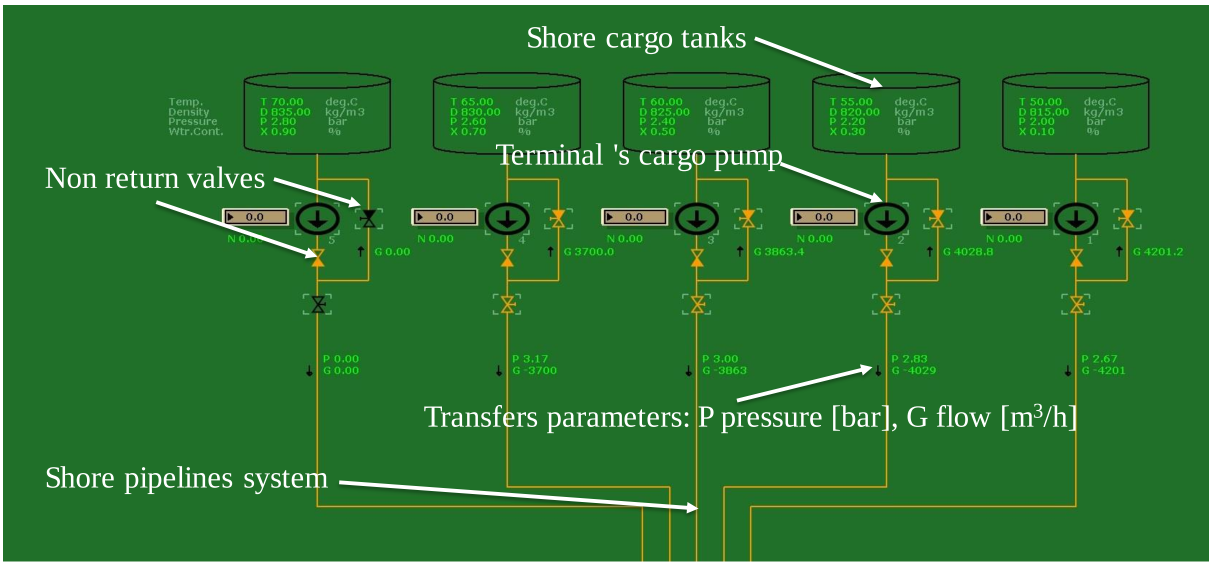

Figure 16. Shore pipelines arrangements [26].

Oil Terminal and VLCC tanker connections are shown in Figure 17. Close to the connected loading arms there are connected elements of ESD system to improve the safety during cargo transfer. Such systems should be always tested before commencing of the cargo operations, to confirm that every elements of this system is working properly.

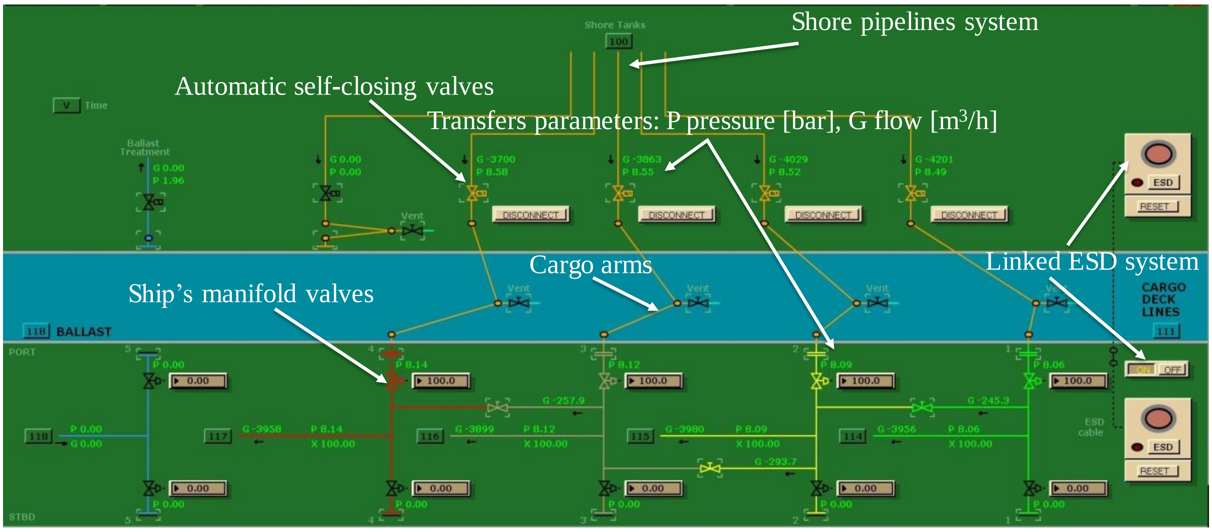

Figure 17. Active ESD system with an automatic self-closing valve [26].

Figure 18 presents cargo pump together with elements of the Automatic Unloading System, which allowed to empties the cargo tanks. AUS automatically reduce speed cargo pumps, adjust the discharging valve when the suction pressure drop down in cargo line or when the level in separator drop below setting limit.

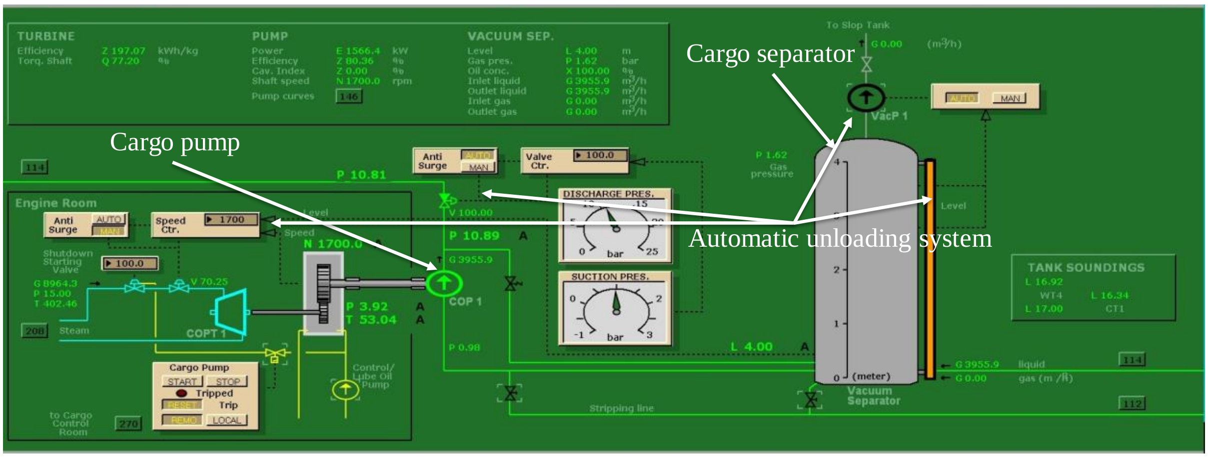

Figure 18. Centrifugal ships cargo pump with arrangements [26].

7.1.2. Ship/Shore Link

The purpose of the SSL is to transmit, without delay, a signal from ship to terminal or vice versa. For oil and chemical transfers, the minimum recommendation is to use an electric SSL that incorporates a 5-pin twist connector.

Figure 19. Approved 5-pin twist connectors for ESD system [5].

7.1.3. ESD recommendation according to OCIMF

For transfer operations involving oil and chemicals, including ship to ship transfers, linked ESD systems should be provided and used.
ESD recommendation according to OCIMF are [18]:

- Ship and terminal ESD systems should be linked via an electrical umbilical, provided by the terminal, that uses recommended 5-pin twist connectors;
- The ESD link should be capable of being manually activated, as a minimum;
- The linked ESD system must be tested regularly. Contingency plans should be in place in case of failure of the linked ESD system;
- Any modifications to the system should follow strict procedures and be documented in full;
- Functional flowchart of the linked ESD and related systems should be available in the terminal control room and in the Terminal Information Book provided to visiting ships;
- Linked ESD systems should pass ESD signals in both directions, e.g. from terminal to ship and from ship to terminal;
- Terminals should arrange for surge calculations to be made as part of the hydraulic analysis of their specific pipeline and cargo transfer systems to establish the maximum safe flow rate. The output from hydraulic analysis should be considered when deciding the appropriate ESD options for each berth.

7.1.4. Configuration of a linked ship/shore ESD system

The standard oil terminal configuration comprises:

- terminal control unit for installation in the terminal's control room;
  connected to
  - jetty control unit;
  connected to
  - ship/shore umbilical cable fitted with a recommended male 5-pin twist connector.

The standard ship configuration comprises:

- ship control unit, for installation in the ship's control room;
  connected to
  - ship side box fitted with fixed recommended female 5-pin socket assemblies for installation in the ship's manifold area, port and starboard.

In most popular solution both system of ESD from oil terminal and oil tanker are connected by umbilical cable before cargo operation commence. Both units are equipped with approved 5-pin twist sockets for connectors. Instead of cable connection there are also possibility to pair both systems using the wireless connection. An example of such ship/shore ESD configuration is presented in Fig. 20.

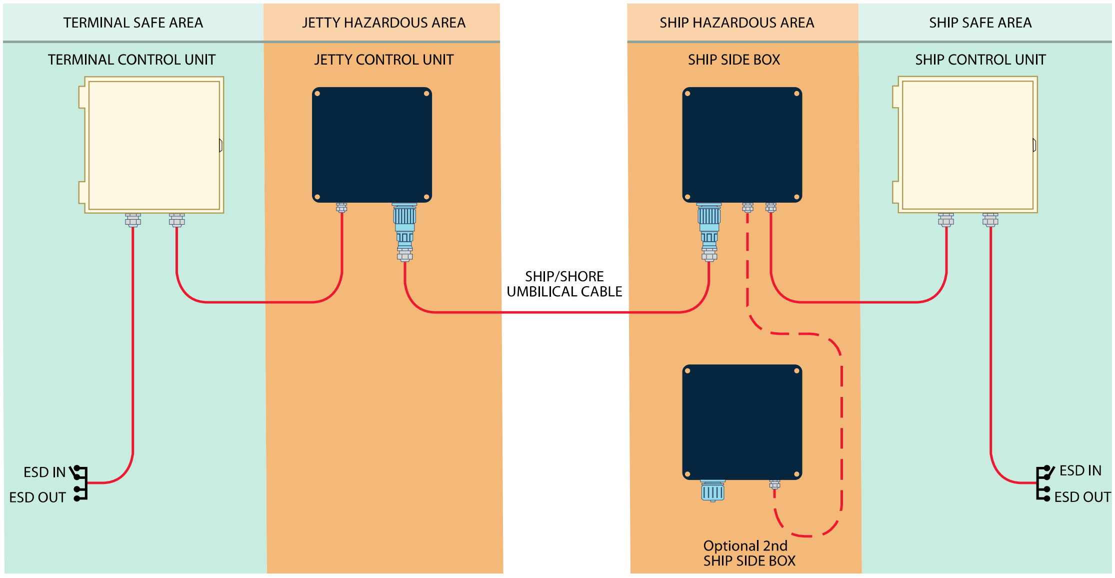

Figure 20. Active ESD system with cable connection [5].

7.2. Prevention of pressure upsurge inside the pipelines

One of important causes of oil spill, mentioned before, is pressure upsurge inside a pipeline generated by an abrupt change in the rate of flow of liquid in the line i.e. as a hydraulic hammer's consequence [2], [23]. A hydraulic hammer can be caused by the ship's breakaway couplings when the ship disconnects or from an Emergency Shut Down (ESD) System activated valve closure (Fig. 21).

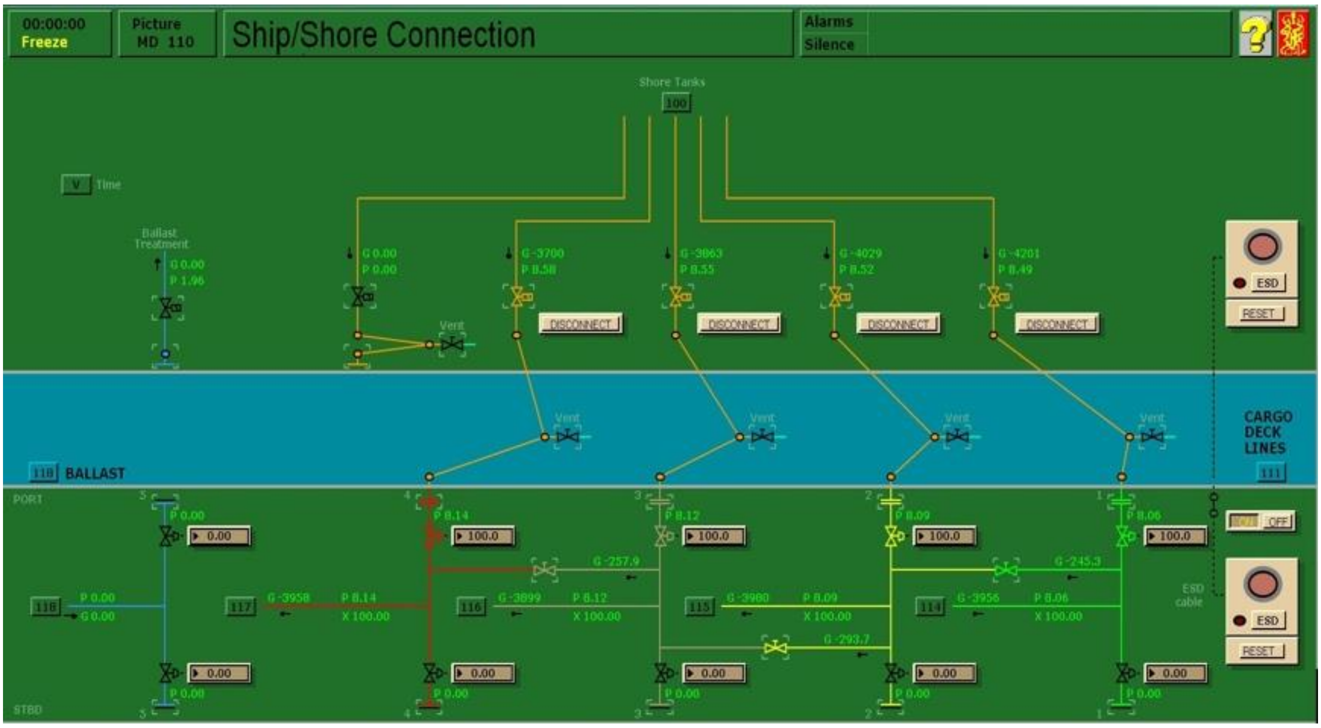

Figure 21. Active ESD system with an automatic self-closing valve [26].

Both can cause damage to loading hoses or loading arms, loading buoys, and feed pipework. Sudden valve closure on the reloading installation may occur e.g. on a ship that has all the cargo tanks full. Such situation may take place when there is no more space to accept additional volumes of crude oil and there is no more possibility to pass the information to the terminal to stop the transfer cargo, this may happen when the both, primary and backup communication system failed.

In this case, if there is an emergency system to stop handling, not to cause overflow tanks and bottling, the ship decides to close the valve connecting it to the mainland, resulting in the so-called "hammering" and discontinuity of installation and spill [12].

The pressure surge in the pipelines may result in pressure stresses or displacement stresses, and as a consequence it may cause a rupture leading to an extensive oil spill. According to [29], a pressure surge during tanker loading can occur as a result of:

- closure of an automatic shutdown valve,
- slamming shut of a shore non-return valve,
- slamming shut of a butterfly type valve,
- rapid closure of a power operated valve.

To protect terminal from the potential damage that can be caused by pressure surges, some pressure relief systems and systems of the non-return valves installed on pipelines are often used (Fig. 22).

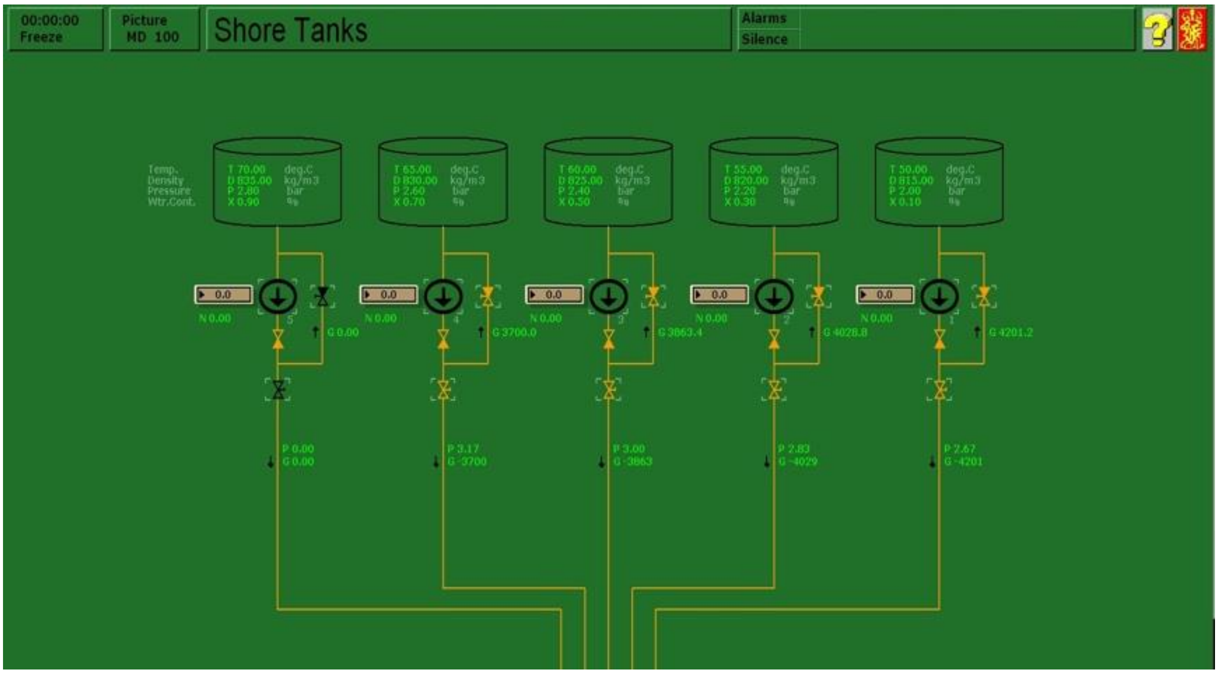

Figure 22. Shore cargo tanks arrangement with non-return valves on the cargo pipelines [26].

Excessive surge pressures result from a sudden change in fluid velocity and, without surge relief, they can damage pipes, other piping components, equipment and personnel. These pressure surges can be generated by anything that causes the liquid velocity in a line to change quickly (e.g., valve closure, pump trip, ESD closure occurs) and subsequently packing pressure. The task of crude oil surge-relief system is to protect both tankers and marine facilities against hydraulic transient pressure surges that can occur during cargo operations. Such system should be able to open very quickly high capacity valves to remove surge pressures from the line and then stop or return to the normal state if all parameters of cargo transfer comeback to acceptable value.

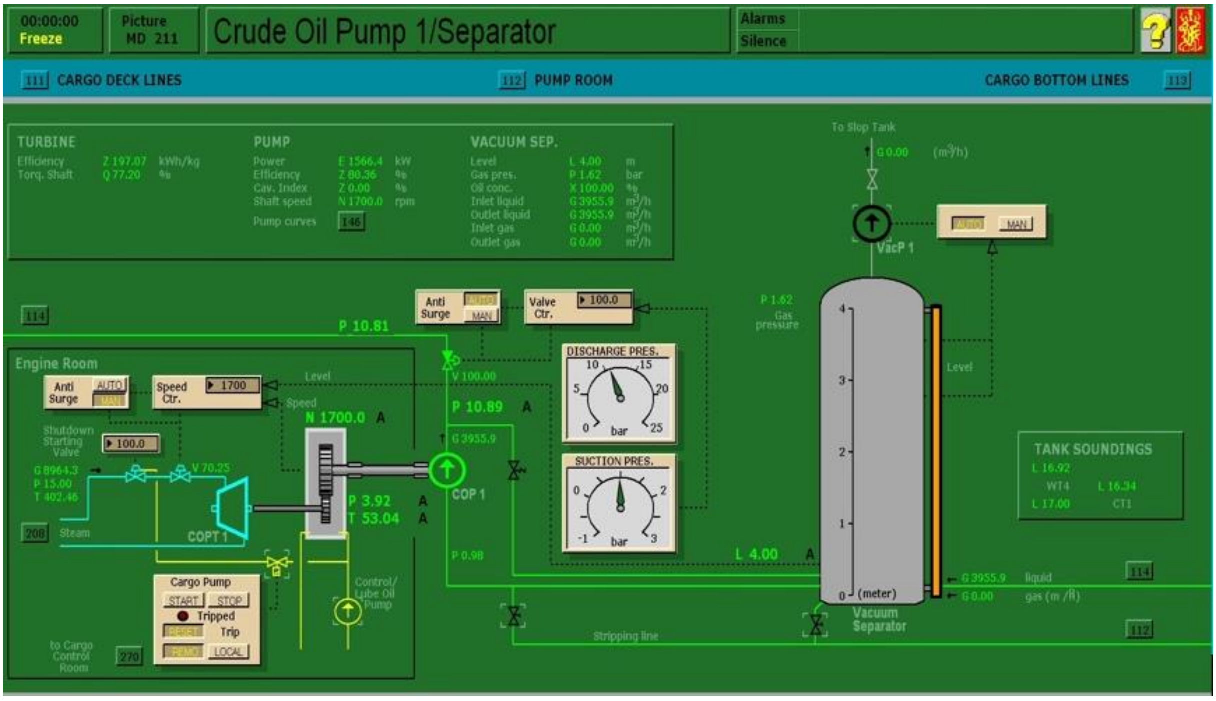

Figure 23. Centrifugal cargo pump arrangement with pressure relief and non-return valves [26].

Typical tank and pressure vessel systems are required to release pressure without passing large volumes of liquid. These valves are often fully open to allow the entire stream flowing. Closing of these valves should also be done quickly but without causing additional pressure surge. To prevent hydraulic shock and secondary surge during a valve closing, some surge relief systems include damping or slowing systems on valve closing [8]. As example (Fig. 23), above showed typical arrangement to protect cargo pump against pressure surges from shore side.

Investigation reports after oil spills in ports or oil terminals indicate also a problem of organizational and safety culture. We also analysed the investigation report on a refinery explosion caused by a raffinate splitter tower overflow.

In order to prevent oil spills accidents following recommendations are given:

- adequately addressed controlling major hazard risk,
- creating an effective reporting and learning culture after oil spill incidents,
- incorporating human factor considerations in its training, staffing, and work schedule for operations personnel,
- training courses including abnormal and emergency situations and procedures of reaction in such situations,
- proper communication (eliminating problems associated with communication) between operators from the vessel and terminal responsible for oil transfer,
- providing effective safety culture leadership and oversight,
- providing adequate resources to prevent major accidents,
- avoiding excessive cost-cutting.

Some of these recommendations could be realized on Liquid Cargo Handling Simulators as some specific scenarios dedicated for few emergency accidents, which appears frequently during the cargo operations [30]. Many tankers operators organize training or required such training from every new officer joining the company. Developed Safety Management System on board of the tankers required that some training for officers should be regularly renewed after 4-5 years, to be comply with Company's and charterers procedures.

LCH Simulator's training for shore personnel involved in cargo operations in oil terminal is a good advantage, many often allowed them to understand many decisions on the ship's side. Special training dedicated for terminal staff should include initial and final parts of each cargo operations, together with the relevant check lists and emergency situations during cargo operation, scenarios such manifold or cargo valve leakage, unexpected vapour gas release, emergency stop and emergency shut down with all proper activities, which should be undertaken during above mentioned incidents. All exercises should be conducted by experienced instructor with comments, assessments and open discussion after completion of each part of such training.

7.3. Solutions related to human factor (procedures and training courses)

In the practical part of the study, due to the extremely important role of the human factor during the transfer of crude oil at the terminal, the most important provisions regarding safe oil transfer, from Ship/Shore Safety Check List (SSSCL), are quoted.

The basic method to reduce possibility of human erroneous among the crewmembers is regular skills improvement. The simplest option to gain experience in safe and controlled conditions is utilization of the simulators. Possibility to make a mistake, even lead to the accident or oil spill during the exercises could improve the knowledge of the trainees and prevent repetition of the same situation in the reality.

Therefore, in addition to the safety procedures on crude oil transfer, we recommend courses on the Liquid Cargo Handling Simulator (LCHS) in the form of films with instructions on how to deal with various possible situations that occurred during oil transfer at the terminal. These courses relate to the situation of the oil terminal and the tanker and show what is happening when someone emendrates closes and opens the valves with or without the ESD system activation. Our approach to training on LCH Simulator is shown in the diagram in Fig. 24.

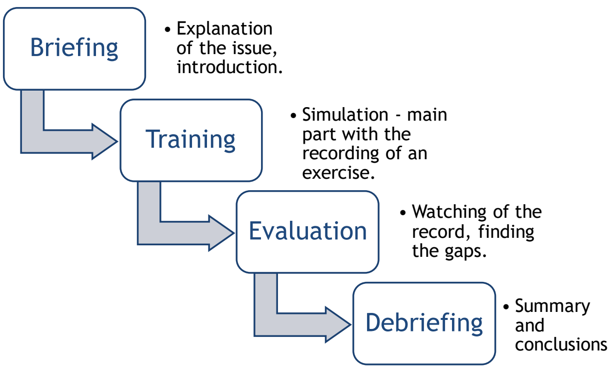

Figure 24. Approach to training on LCHS presented in the study.

7.3.1. Safety procedures during liquid cargo transfers – Ship/Shore Safety Check List

We start with the overview of the guidelines ans procedures given in International Safety Guide for Oil Tankers & Terminals (ISGOTT). ISGOTT includes standard and major reference to safety onboard tankers and oil terminals. Document was prepared in collaboration of the International

Chamber of Shipping (ICS) with the Oil Companies International Marine Forum (OCIMF) and the International Association of Ports and Harbors (IAPH). ISGOTT is a guide and does not impose obligations on involved parties. However, meeting its requirements is unwritten rule for the major oil companies to keep the highest quality of work and safety standards. To maintain the status of major safety guidelines, every edition of ISGOTT is updated to the most modern technologies and latest legislation issues.

The last edition of ISGOTT is divided into four main parts:

1. General information – contains basic information on the treatment of petroleum, its derivatives and their physical/chemical properties. Special attention should be paid to flammability and toxicity, as well as to the danger associated with electricity in the area of explosive gases.
2. Tanker information – presents the safety aspects of the ship. Includes procedures for enclosed space entry or storing dangerous goods. Human factor is also taken into account - fatigue and drugs policy are discussed.
3. Terminal information – concerns the organization and security of the terminal and equipment for the ship. Guidelines for loading and discharging, as well as organization of evacuation can be found.
4. Management of the tanker and terminal interface – contains situations in which both the ship and the shore are involved, such as communication, mooring and unmooring. An example of the Ship/Shore Safety Checklist was presented, and the procedures were described in the event of a fire or explosion.

Ship/Shore Safety Check List (*SSSCL*) is a list of checks corresponding to the preparation of safe transfer of liquid cargo between tanker and the terminal. The responsibility and accountability for the safe conduct of operations while a ship is at an oil terminal are shared jointly between the ship's Master (or his representative) and the Terminal Representative.

Safety procedures and regulations cited below pay particular attention to the responsibility and accountability for the safe conduct of operations while a ship is at an oil terminal are shared jointly between the ship's Master or Chief Officer and the Terminal Representative.

Before commencement of cargo or ballast operations, the Master, or his representative, and the Terminal Representative should:

- Agree in writing on the transfer procedures, including the maximum loading or unloading rates.
- Agree in writing on the action to be taken in the event of an emergency during cargo or ballast handling operations.
- Complete and sign the SSSCL.

Figure 25 shows Tanker – Oil terminal interface.

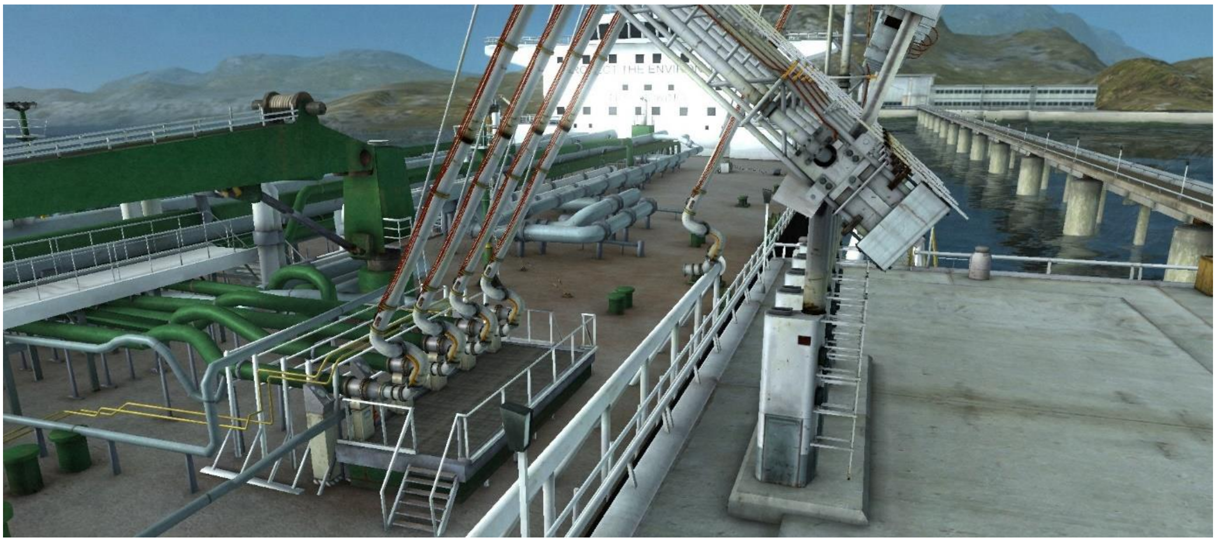

Figure 25. Crude Oil Tanker – Oil Terminal interface [26].

SSSCL comprises four main parts (A-D):

- Part A – physical checks for transfer of Bulk Liquids (applicable to all operations);
- Part B – verbal checks for transfer of Bulk Liquids (applicable to all operations);
- Part C – additional requirements for transfer of Bulk Liquid Chemicals;
- Part D – additional requirements for transfer of Bulk Liquefied Gases.

Coding of items inside the checklist:

- A (Agreement) – this indicates an agreement or procedure that should be identified in the Remarks column of the SSSCL or communicated in some other mutually acceptable form;
- P (Permission) – in the case of a negative answer to the statements coded P, operations should not be conducted without the written permission from the appropriate authority;
- R (Re-check) – this indicates items to be re-checked at appropriate intervals, as agreed between both parties, at periods stated in the declaration.

The joint declaration should not be signed until both parties have checked and accepted their assigned responsibilities and accountabilities.

Selected critical safety issues from SSSCL, regarding the transfer of crude oil between tanker and oil terminal, are listed below. We start with the first group of regulations, i.e. Part A Bulk Liquid General. The quoted procedures and regulations have saved their original numbers from the source document (ISGOTT), so that the reader can easily refer to the SSSCL document from which they originate.

SSSCL Part A – Bulk Liquid General - physical checks

3. The agreed ship/shore communication system is operative.

“Communication should be maintained in the most efficient way between the responsible officer on duty on the ship and the responsible person ashore.

When telephones are used, the telephone both on board and ashore should be continuously manned by a person who can immediately contact his respective supervisor.

Additionally, the supervisor should have a facility to override all calls. When RT/VHF systems are used, the units should preferably be portable and carried by the supervisor or a person who can get in touch with his respective supervisor immediately. Where fixed systems are used, the guidelines for telephones should apply.

The selected primary and back-up systems of communication should be recorded on the check list and necessary information on telephone numbers and/or channels to be used should be exchanged and recorded. The telephone and portable RT/VHF systems should comply with the appropriate safety requirements.”

7. The ship’s cargo and bunker hoses, pipelines and manifolds are in good condition, properly rigged and appropriate for the service intended.

“Hoses should be in a good condition and properly fitted and rigged so as to prevent strain and stress beyond design limitations.

All flange connections should be fully bolted and any other types of connections should be properly secured.

Hoses and pipelines should be constructed of a material suitable for the substance to be handled, considering its temperature and the maximum operating pressure.

Cargo hoses should be indelibly marked so as to allow the identification of the products for which they are suitable, specified maximum working pressure, the test pressure and last date of testing at this pressure, and, if used at temperatures other than ambient, maximum and minimum service temperatures.”

8. The terminal’s cargo and bunker hoses or arms are in good condition, properly rigged and appropriate for the service intended.

“Hoses should be in a good condition and properly fitted and rigged so as to prevent strain and stress beyond design limitations.

All flange connections should be fully bolted and any other types of connections should be properly secured.

Hoses/arms should be constructed of a material suitable for the substance to be handled, considering its temperature and the maximum operating pressure.

Cargo hoses should be indelibly marked so as to allow the identification of the products for which they are suitable, specified maximum working pressure, the test pressure and last date of testing at this pressure, and, if used at temperatures other than ambient, maximum and minimum service temperatures.”

9. The cargo transfer system is sufficiently isolated and drained to allow safe removal of blank flanges prior to connection.

“A positive means of confirming that both ship and shore cargo systems are isolated and drained should be in place and used to confirm that it is safe to remove blank flanges prior to connection. The means should provide protection against:

- pollution due to unexpected and uncontrolled release of product from the cargo system,
- injury to personnel due to pressure in the system suddenly being released in an uncontrolled manner.”

13. The ship’s unused cargo and bunker connections are properly secured with blank flanges fully bolted.

“Unused cargo and bunker line connections should be closed and blanked. Blank flanges should be fully bolted and other types of fittings, if used, properly secured."

Figure 26. Unused cargo connections properly secured.

14. The terminal's unused cargo and bunker connections are properly secured with blank flanges fully bolted.
"Unused cargo and bunker connections should be closed and blanked.
Blank flanges should be fully bolted and other types of fittings, if used, properly secured."

16. Sea and overboard discharge valves, when not in use, are closed and visibly secured.
"Experience shows the importance of this item in pollution avoidance on ships where cargo lines and ballast systems are interconnected.
Remote operating controls for such valves should be identified in order to avoid inadvertent opening. If appropriate, the security of the valves in question should be checked visually."

Figure 27. OBV closed and properly secured.

SSSCL Part B – Bulk Liquid General- verbal verification

22. There is an effective deck watch in attendance on board and adequate supervision of operations on the ship and in the terminal.
"The operation should be under constant control and supervision on ship and ashore.
Supervision should be aimed at preventing the development of hazardous situations. However, if such a situation arises, the controlling personnel should have adequate knowledge and the means available to take corrective action. The controlling personnel on the ship and in the terminal should maintain effective communications with their respective supervisors.
All personnel connected with the operations should be familiar with the dangers of the substances handled and should wear appropriate protective clothing and equipment."

23. There are sufficient personnel on board and ashore to deal with an emergency.
"At all times during the ship's stay at the terminal, a sufficient number of personnel should be present on board the ship and in the shore installation to deal with an emergency."

24. The procedures for cargo, bunker and ballast handling have been agreed.
"The procedures for the intended operation should be pre-planned. They should be discussed and agreed upon by the Responsible Officer and Terminal Representative prior to the start of the operations. Agreed arrangements should be formally recorded and signed by both the Responsible Officer and Terminal Representative. Any change in the agreed procedure that could affect the operation should be discussed by both parties and agreed upon. After both parties have reached agreement, substantial changes should be laid down in writing as soon as possible and in sufficient time before the change in procedure takes place. In any case, the change should be laid down in writing within the working period of those supervisors on board and ashore in whose working period agreement on the change was reached.
The operations should be suspended and all deck and vent openings closed on the approach of an electrical storm.
The properties of the substances handled, the equipment of ship and shore installation, and the ability of the ship's crew and shore personnel to execute the necessary operations and to sufficiently control the operations are factors which should be considered when ascertaining the possibility of handling a number of substances concurrently.

The manifold areas, both on board and ashore, should be safely and properly illuminated during darkness.
The initial and maximum loading rates, topping-off rates and normal stopping times should be agreed, having regard to:

- the nature of the cargo to be handled,
- the arrangement and capacity of the ship's cargo lines and gas venting systems,
- the maximum allowable pressure and flow rate in the ship/shore hoses and loading arms,
- precautions to avoid accumulation of static electricity,
- any other flow control limitations.

A record to this effect should be formally made as above."

25. The emergency signal and shutdown procedure to be used by the ship and shore have been explained and understood.
"The agreed signal to be used in the event of an emergency arising ashore or on board should be clearly understood by shore and ship personnel. An emergency shutdown procedure should be agreed between ship and shore, formally recorded and signed by both the ship and terminal representative.
The agreement should state the circumstances in which operations have to be stopped immediately.
Due regard should be given to the possible introduction of dangers associated with the emergency shutdown procedure."

30. The requirements for closed operations have been agreed.
"It is a requirement of many terminals that when the ship is ballasting, loading or discharging, it operates without recourse to opening ullage and sighting ports. In these cases, ships will require the means to enable closed monitoring of tank contents, either by a fixed gauging system or by using portable equipment passed through a vapour lock, and preferably backed up by an independent overfill alarm system."

31. The operation of the P/V system has been verified.
"The operation of the P/V valves and/or high velocity vents should be checked using the testing facility provided by the manufacturer. Furthermore, it is imperative that an adequate check is made, visually or otherwise, to ensure that the checklift is actually operating the valve. On occasion, a seized or stiff vent has caused the checklift drive pin to shear and the ship's personnel to assume, with disastrous consequences, that the vent was operational."

Figure 28. P/V valve.

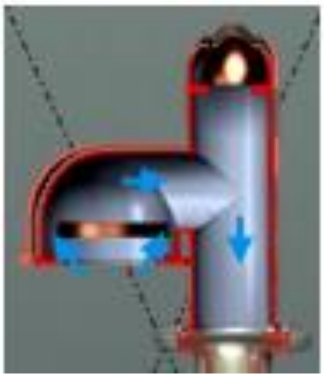

Figure 29. P/V valve opened.

Figure 30. P/V valve setting.

Before loading operations all P/V valves should be tested manually – see Movie 1.

32. Where a vapour return line is connected, operating parameters have been agreed.
"Where required, a vapour return line will be used to return flammable vapours from the cargo tanks to shore. The maximum and minimum operating pressures and any other constraints associated with the operation of the vapour return system should be discussed and agreed by ship and shore personnel."
An exemplary vapour return system connection is shown in Fig. 31.

Figure 31. Vapour return line connection on tanker's manifold.

33. Independent high-level alarms, if fitted, are operational and have been tested.
"Owing to the increasing reliance placed on gauging systems for closed cargo operations, it is important that such systems are fully operational and that back-up is provided in the form of an independent overfill alarm arrangement. The alarm should provide audible and visual indication and should be set at a level which will enable operations to be shut down prior to the tank being overfilled. Under normal operations, the cargo tank should not be filled higher than the level at which the overfill alarm is set.
Individual overfill alarms should be tested at the tank to ensure their proper operation prior to commencing loading unless the system is provided with an electronic self-testing capability which monitors the condition of the alarm circuitry and sensor and confirms the instrument set point."
Figure 32 presents tank's high-level and tank overfill alarm panel

Figure 32. Tank high-level and tank overfill alarm panel.

35. Shore lines are fitted with a non-return valve, or procedures to avoid back filling have been discussed.

"In order to avoid cargo running-back when discharge from a ship is stopped, either due to operational needs or excessive back pressure, the terminal should confirm that it has a positive system which will prevent unintended flow from the shore facility onto the ship. Alternatively, a procedure should be agreed that will protect the vessel."
Figure 33 presents fragment of shore pipelines protected by non-return valves.

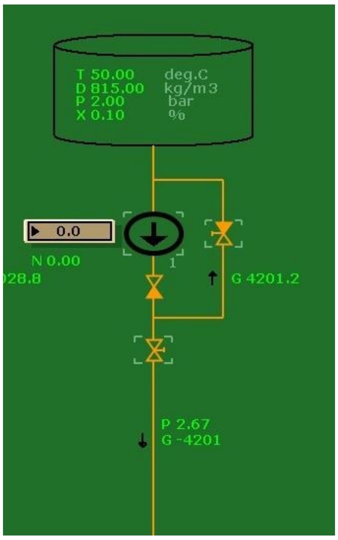

Figure 33. Shore pipeline installation with valves arrangements.

41. Portable VHF/UHF transceivers are of an approved type.
"Portable VHF/UHF sets should be of a safe type, approved by a competent authority. VHF radio telephone sets may only operate in the internationally agreed wave bands. Equipment should be well maintained. Damaged units, even though they may be capable of operation, should not be used."

Figure 34. Intrinsically safe portable VHF/UHF transceivers.

48. The maximum wind and swell criteria for operations have been agreed.
"There are numerous factors which will help determine whether cargo or ballast operations should continue.

Discussion between the terminal and the ship should identify limiting factors which could include:

- wind speed/direction and the effect on hard arms,
- wind speed/direction and the effect on mooring integrity,
- wind speed/direction and the effect on gangways,
- swell effects at exposed terminals on mooring integrity or gangway safety.

Such limitations should be clearly understood by both parties.
The criteria for stopping cargo, disconnecting hoses or arms and vacating the berth should be written in the 'Remarks' column of the check list."

50. The IGS (Inert Gas System) is fully operational and in good working order.
"The inert gas system should be in safe working condition with particular reference to all interlocking trips and associated alarms, deck seal, non-return valve, pressure regulating control system, main deck IG line pressure indicator, individual tank IG valves (when fitted) and deck P/V breaker.
Individual tank IG valves (if fitted) should have easily identified and fully functioning open/close position indicators."
Figure 35 presents working IGS during cargo discharge.

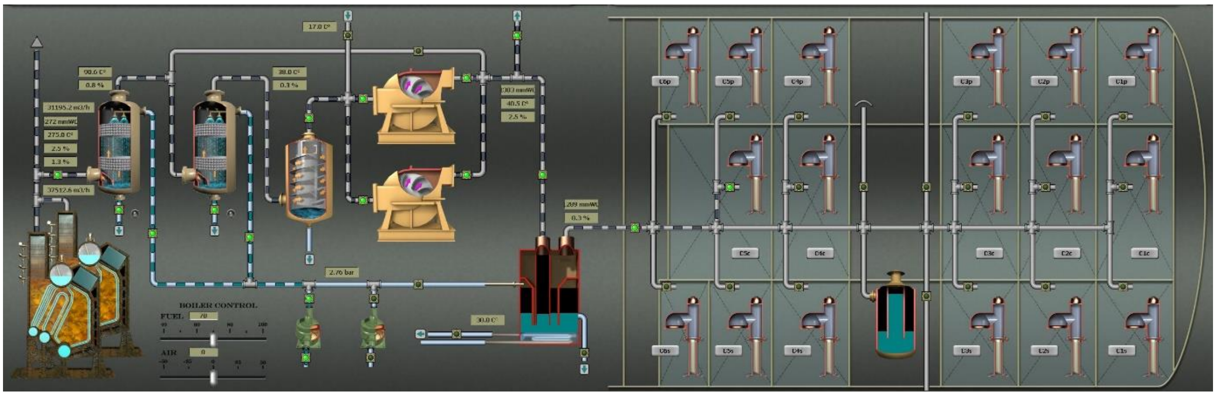

Figure 35. IGS supplying Inert Gas to the cargo tanks during discharge operation.

51. Deck seals, or equivalent, are in good working order.
"It is essential that the deck seal arrangements are in a safe condition. In particular, the water supply arrangements to the seal and the proper functioning of associated alarms should be checked."

Figure 36. Deck seal.

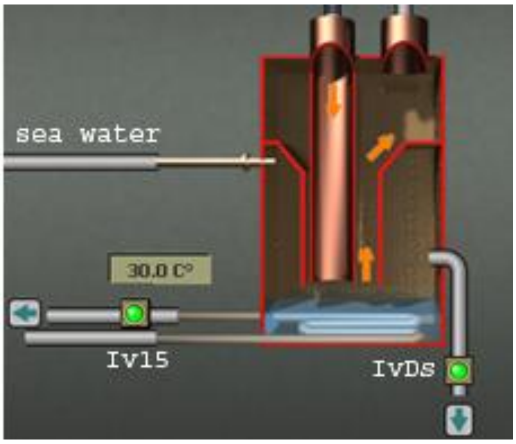

Figure 37. Deck seal connections.

52. Liquid levels in pressure/vacuum breakers are correct.
"Checks should be made to ensure that the liquid level in the P/V breaker complies with manufacturer's recommendations."

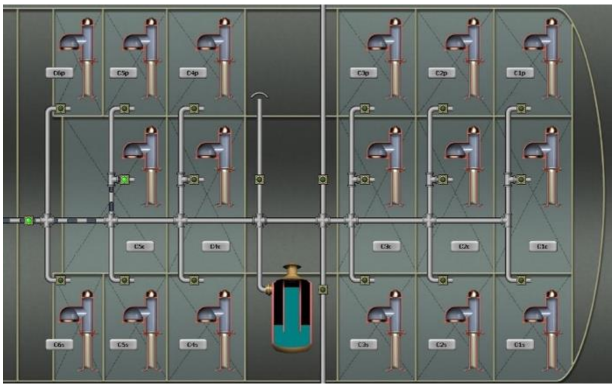

Figure 38. IGS distribution on deck with P/V breaker.

54. All the individual tank IG valves (if fitted) are correctly set and locked.
"For both loading and discharge operations it is normal and safe to keep all individual tank IG supply valves (if fitted) open in order to prevent inadvertent under or over pressurisation.
In this mode of operation, each tank pressure will be the same as the deck main IG pressure and thus the P/V breaker will act as a safety valve in case of excessive over or under pressure.
If individual tank IG supply valves are closed for reasons of potential vapour contamination or de-pressurisation for gauging, etc., then the status of the valve should be clearly indicated to all those involved in cargo operations. Each individual tank IG valve should be fitted with a locking device under the control of a responsible officer."
Figure 39 presents atmosphere of cargo tank depends of the different operation during ship's exploitation.

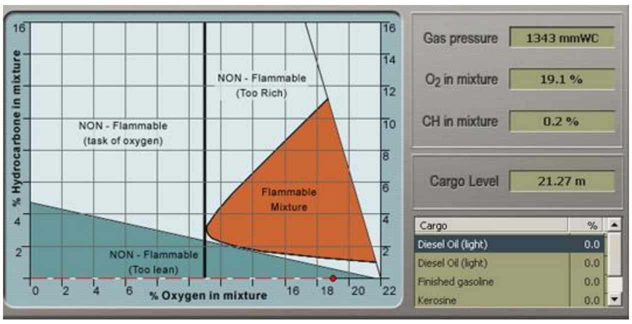

Figure 39. Gas concentration in atmosphere in the cargo tank.

55. All personnel in charge of cargo operations are aware that, in the case of failure of the inert gas plant, discharge operations should cease and the terminal be advised.
"In the case of failure of the IG plant, the cargo discharge, de-ballasting and tank cleaning should cease and the terminal to be advised.
Under no circumstances should the ship's officers allow the atmosphere in any tank to fall below atmospheric pressure."

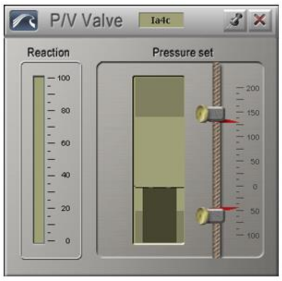

Figure 40. Pressure limit setting for P/V valves.

SSSCL Part C – Bulk Liquid Chemicals – verbal verification

5. The cargo handling rate is compatible with the automatic shutdown system, if in use.
"Automatic shut down valves may be fitted on the ship and ashore. The action of these is automatically initiated, for example, by a certain level being reached in the ship or shore tank being filled.
Where such systems are used, the cargo handling rate should be established to prevent pressure surges from the automatic closure of valves causing damage to ship or shore line systems. Alternative means, such as a re-circulation system and buffer tanks, may be fitted to relieve the pressure surge created.
A written agreement should be made between the ship and shore supervisors indicating whether the cargo handling rate will be adjusted or alternative systems will be used."
The maximum allowable pressure is given by the formula [11]

$$\Delta P_{\max} = \rho c v_{\max}, \tag{106}$$

where:
$\Delta P_{\max}$ – maximum pressure increase in the pipeline [*Pa*];
ρ – oil density 850.0 [kg/m^3];
c – velocity of sound propagation in petroleum charge 1300 [*m/s*];
$v_{\max}$ – maximum liquid speed [*m/s*].
The maximum permissible volumetric flow rate is [11]

$$Q_{\max} = \frac{\pi d^2 v_{\max}}{4} = \frac{\pi d^2 \Delta P_{\max}}{4\rho c} = 0.025 d^2 \Delta P_{\max}, \tag{107}$$

where:
$Q_{\max}$ – transfer rate [m^3/h];
d – diameter pipeline [*m*];

ΔP_{max} – maximum pressure increase in the pipeline [Pa].

6. Cargo system gauges and alarms are correctly set and in good order.
"Ship and shore cargo system gauges and alarms should be regularly checked to ensure they are in good working order. In cases where it is possible to set alarms to different levels, the alarm should be set to the required level."

Figure 41. High-level and tank overfill alarm panel.

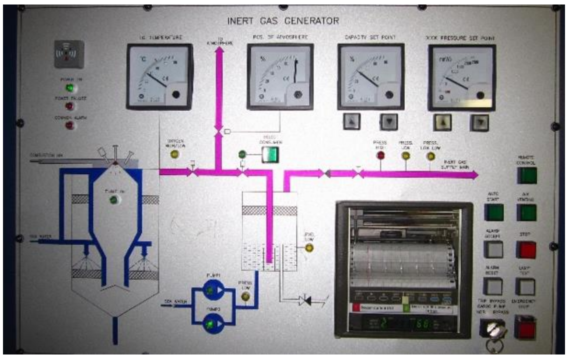

Figure 42. IGS alarm panel.

10. Cargo handling is being performed with the permanent installed pipeline system.
"All cargo transfer should be through permanently installed pipeline systems on board and ashore.
Should it be necessary, for specific operational reasons, to use portable cargo lines on board or ashore, care should be taken to ensure that these lines are correctly positioned and assembled in order to minimise any additional risks associated with their use. Where necessary, the electrical continuity of these lines should be checked and their length should be kept as short as possible. The use of non-permanent transfer equipment inside tanks is not generally permitted unless specific approvals have been obtained. Whenever cargo hoses are used to make connections within the ship or shore permanent pipeline system, these connections should be properly secured, kept as short as possible and be electrically continuous to the ship and shore pipeline respectively. Any hoses used must be suitable for the service and be properly tested, marked and certified."

7.3.2. Safety procedures during cargo loading – Courses on the LCH Simulator

Gdynia Maritime University has got the facilities to provide the trainings for the tankers' crew, as well as the terminal workers. The two Liquid Cargo Handling Simulators (LCHS) allow to carry out advanced trainings for the different types of liquid cargo. The software and the interface of LCHSs (Fig. 43) is similar to the cargo computers used in the CCRs (Cargo Control Rooms) onboard tankers or gas carriers.

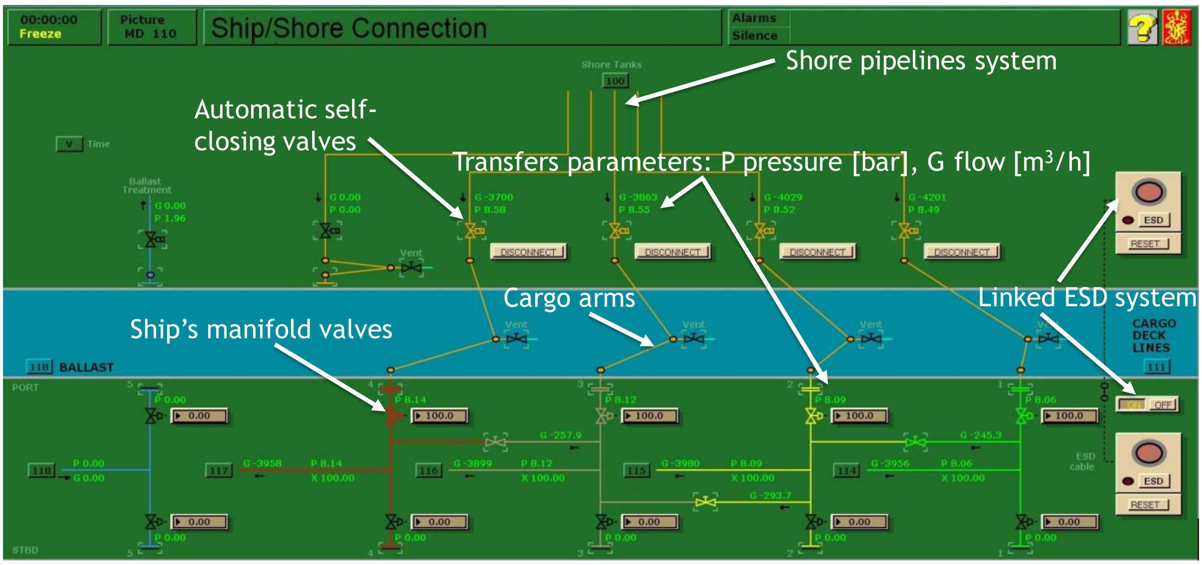

Figure 43. Oil Terminal & VLCC tanker connections – LCHS view.

Movie 2, attached to the report, shows preparations for loading tanker using single shoreline from oil terminal. It includes operations and checks listed below, performed by the terminal operators:

- line-up cargo line in oil terminal,
- check all valves on shore pipeline to cargo manifold,
- check all controls on shore pipelines,
- fill up cargo pumps with cargo,
- start cargo pump with minimum capacity,
- check once again all controls on shore pipelines,
- open discharging valve,
- open terminal manifold valve,
- wait for confirmation from tanker that cargo is received,
- wait for test ESD activated from tanker,
- observed test results, confirm alarms,
- reset all setting to the normal mode,
- wait for tanker readiness to receiving cargo.

Movie 3 attached to the report, shows preparations for loading tanker using single shoreline from oil terminal. It includes operations and checks listed below, performed by the crew on board the tankers.

Preparations for loading tanker using single loading cargo line from oil terminal include:

- line-up cargo line for loading,
- check all valves from designated cargo tanks to ship's manifold,
- check all controls on cargolines,
- open cargo manifold,
- check all valves on cargo manifolds,
- check all gauges on cargo manifolds,
- check the pressure in presently loading tank,
- confirm to terminal that cargo is received,
- test ESD (to stop shore cargo pumps) before loading,
- observed test results, confirm alarms,
- reset all setting to the normal mode,
- confirm to the oil terminal readiness to receiving cargo.

7.3.3. Safety procedures during cargo discharging – Courses on the LCH Simulator

Movie 4 and 5 show preparations for discharging tanker using single cargo line to oil terminal. Movie 4 includes operations performed by the terminal operators and Movie 5 by the tanker operators. They include all operations and checks listed below, performed by the crew on board the tankers or by terminal's personnel accordingly.

Preparations for discharging tanker using single loading cargo line to oil terminal shown on Movie 4:

- line-up shore cargo line in oil terminal,
- check all valves on shore pipeline from shore tank to the cargo manifold,
- check all controls on shore pipelines and shore tanks,
- open slowly terminal manifold valve,
- confirm terminal's readiness to receiving cargo,
- confirm to the tanker that cargo is received,
- test ESD (to stop ship's cargo pumps) before unloading,
- observed test results, confirm alarms,
- reset all setting to the normal mode,
- wait for tanker readiness to discharging cargo.

Preparations for discharging tanker using single loading cargo line to oil terminal shown on Movie 5:

- line-up cargo line for unloading,
- check all valves from designated cargo tanks to ship's manifold,
- check all controls on cargolines,
- fill up ship's cargo pump and separator with cargo,
- start cargo pump with minimum capacity,
- check once again all controls on ship's cargoline,
- open discharging valve,
- check once again all controls on ship's cargoline,
- open ship's cargo manifold,
- check all valves and gauges on cargo manifolds,
- wait for confirmation that oil terminal is ready to receiving cargo,
- wait for test ESD activated from oil terminal,
- observed test results, confirm alarms,
- reset all setting to the normal mode,
- wait for confirmation that oil terminal is ready to receiving cargo.

7.3.4. ESD Activation - Operational safety procedures with courses on the LCH Simulator

Activation of ESD should trip visual and audible alarms on the ship and terminal and the following actions listed in Table 1 and Table 2. Table 1 includes ESD actions for terminal to ship transfers and Table 2 includes ESD actions for ship to terminal transfers [5].

Table 1. ESD actions for terminal to ship transfers [5].

Ship		Terminal
Transmits ESD trip signal to terminal via SSL.	→	Receives ESD trip signal from ship.
	or	
Receives ESD trip signal from terminal.	←	Transmits ESD trip signal to ship via SSL.
		Stops cargo flow, either by tripping terminal's cargo transfer pumps or by other safe means.
Optional		
Closes ship's manifold valves in a safe manner, taking account of potential surge issues.		Closes terminal's ESD valves in a safe manner, taking account of potential surge issues.

Table 2. ESD actions for ship to terminal transfers [5].

Ship		**Terminal**
Transmits ESD trip signal to terminal via SSL.	→	Receives ESD trip signal from ship.
	or	
Receives ESD trip signal from terminal.	←	Transmits ESD trip signal to ship via SSL.
Stops cargo flow by tripping ship's cargo transfer pumps.		
Optional		
Closes ship's manifold valves in a safe manner, taking account of potential surge issues.		Closes terminal's ESD valves in a safe manner, taking account of potential surge issues.

Table 3. Minimal capability for linked ESD systems [5].

Actions to stop cargo flow	− Enables ship to stop the terminal's cargo transfer pumps or prompts shutdown of terminal system. − Enables terminal to stop ship's cargo transfer pumps.
Activation	− Manual push button. − Automatic shutdown of ship's pumps on terminal tank high level alarm. − Automatic activation if signal is lost, e.g. in event of power failure on ship or in terminal.
ESD linkage achieved by	− Ship/shore electrical umbilical fitted with recommended 5-pin twist connectors.

Recommended minimal capability for linked ESD systems are given in Table 3. According to the OCIMF [5], [18], ESD system should stop the cargo pumps to drop down pressure in the pipelines and close slowly all automatic valves to avoid hydraulic surge in shore pipelines. Before resetting ESD system, all cargo pumps should be off and valves should be kept closed. Next after resetting ESD, terminal and tanker operators can again resumed transfer the cargo. Movies 6, 7 and 8 show the proper actions undertaken by crew of the terminal and tanker personnel after activation of ESD system. Movies present operation of ESD system – shows trip the cargo pump and which valves are automatically close to avoid back flow the cargo in pipelines. Movies 6 and 7 show operations after ESD activation in terminal during cargo discharging and during cargo loading. Movie 8 shows operations after ESD activation by the crew on board the tankers.

7.3.5. Emergency Stop (ES) System – Operational safety procedures with courses on the LCH Simulator

Movies 9 and 10 show the operation of ES system when only one part is equipped with Emergency Stop System. Movie 9 presents operation of ES system activated by terminal and the effects when system is activated during tanker's discharging. Movie 10 presents operation of ES system activated by crew of tanker and the effects when system is activated during tanker's loading.
What happen when only one part (terminal or tanker) activated ES not ESD:

- oil terminal during tanker discharging (Movie 9),
- oil tanker during tanker loading (Movie 10).

The simplest solution of the ESD has been designed for an emergency stop of cargo transfer. However, there are many different factors which could affected the cargo transfer and the effects will be the same when the ESD is not activated. In Table 4 there are listed some others activators, which should be considered at the design stage of the ESD system.

Table 4. Optional activators for ESD [5].

Hazard	**Ship**	**Terminal**
Fire detection	ESD will be activated when fusible links installed in the cargo area are tripped, typically between 98–104°C.	ESD will be activated by the terminal's fire detection system.
Overfilling of tanks	ESD will be activated when the higher of two 'spot' level sensors in each of the ship's cargo tanks is tripped. This high-high level sensor will be independent from the main level measuring system and arranged so that the operation of any one sensor will activate ESD.	
Loss of pressure in cargo valve remote control system	The trip for the ESD will depend on the type of valve actuators used. The trip should be a low-low pressure switch installed in the common supply line downstream of any isolating valve. Pre-alarms should also be fitted and signals should have suitable time delays.	
Excessive pressure in cargo transfer	Pressure sensors in the tanker's discharge pipelines may be pre-set to	Pressure sensors in the terminal's cargo transfer system may be pre-set to activate

system	activate an ESD if they register a pressure in excess of the nominal operating pressure for the cargo transfer system but less than its MAWP.	an ESD if they register a pressure in excess of the nominal operating pressure for the cargo transfer system but less than its MAOP. The optimum siting and setting for these pressure sensors would be determined by hydraulic analysis which includes consideration of surge.
Movement of monitored critical valve in cargo transfer system	ESD is activated when a cargo transfer valve closes, that hydraulic analysis has determined needs to be open for the duration of a transfer operation, e.g. a ROSOV.	ESD is activated when a cargo transfer valve closes, that hydraulic analysis has determined needs to be left in open for the duration of a specific transfer operation.
High level of liquid in surge drum		In terminal cargo transfer systems fitted with surge drums, detection of high liquid levels could activate an ESD.
Exceeding MLA operating limits		MLAs may be designed to activate an ESD when operating envelope limit switches are tripped. Sensors or other trips may be placed at the vertical and horizontal limits of the MLA and may be triggered by sway and surge excursions of the ship at the berth. MLAs may also have ESD activators associated with loss of actuating power to the arms or ancillary equipment.
Activation of MLA PERC		ESD activation should precede PERC activation. PERCs may be activated either manually or when MLA operating envelope limit switches have been tripped.

The most common solution is using the Dead Man Alarm system in addition to ESD, which guarantees the presence of personnel from the terminal and the tanker near the manifold area and a readiness to act in an emergency situation.

After the activation of the standby system, confirmation of the presence of the crew in the vicinity of connections is required at agreed time intervals. After exceeding the set time, the system wakes to the alarm mode, the optical signal activates with a growing penetrating sound signal. During a minute, the terminal personnel and / or crew member has the option to deactivate the system by pressing the standby button for 5 seconds, no response from the crew and / or terminal personnel will result in the ESD system being activated. Such a solution ensures constant supervision and monitoring of transshipment operations at the place of a ship-to-terminal connection, which should never remain unattended.

ES and ESD systems in addition to manual activation - by means of a button, can additionally be triggered automatically by a series of sensors installed on the cargo systems. One of the most commonly used solutions is the automatic activation of ES caused by the increase of the cargo pressure in the pipeline caused by accidental or intentional closure of the shut-off valve. Exceeding the set value of the pressure on the sensor located on the manifold or on the pipeline triggers the activation signal of the ESD system. As a result of ESD activation, the work of cargo pumps is stopped, and automatic valves may be closed if they are installed on the cargo system. The method of closing automatic valves should be adjusted so as to minimize the effects of the phenomenon called hydraulic shock, occurring with significant pressure fluctuations in the pipeline system.

In ESD systems used in oil terminals, automatic activation of the system may be caused by exceeding the level of HiHi (98%) filling land tanks or LoLo (2%). Automatic activation of the system can also be related to the closing of automatic valves or the activation of other systems (fast opening fail-safe valve) that release pressure from the pipeline system, and the load should be directed to specially dedicated tanks. In ESD systems used in oil terminals, automatic activation of the system may be caused by exceeding the level of HiHi (98%) filling land tanks or LoLo (2%).

7.3.6. Associated safety systems – Operational safety procedures with courses on the LCH Simulator

In this section, we present the procedure of emergency disconnection of loading arms and describe associated safety systems. For an oil terminal to be able to disconnect loading arms from the ship in an emergency, an Emergency Release System (ERS) should be provided with a PERC incorporated into each arm. This allows disconnection with minimum spillage, known as the dry-break concept. The ERS should only be activated after the ESD has been activated.

The sequence of actions on the terminal is as follows:

1. ESD activated (either on the terminal or ship, manually or automatically).
2. ERS activated (either manually or automatically).
3. ERS valves close (automatically).
4. PERC activated (automatically).
5. Loading arms disconnected (automatically).

It is recommended that when an ERS is activated a loud audible and highly visible alarm is triggered on the jetty. This will warn personnel to stand clear of the ship's manifold area and the jetty working platform. After Emergency Release System activated either manually or automatically, loading arms are disconnected. System ERS allows for quick and safe disconnecting a loading arm from a ship with minimal product spillage. It consists of an emergency release coupler between two interlocked block valves.

Movie 11 shows how to perform properly the above-mentioned actions on the oil terminal during the emergency disconnection of loading arms.

Considering associated safety systems, some oil terminal arrangements incorporate a surge relief system. At loading terminals, this may comprise a fast opening fail-safe dump valve that diverts liquid flow to a surge drum while the ESD and ERS valves are closing, minimising surge.

Movie 12 shows how to ship's or terminal unloading system properly perform the actions when the discharging pressure rapidly increase in cargo pipelines.

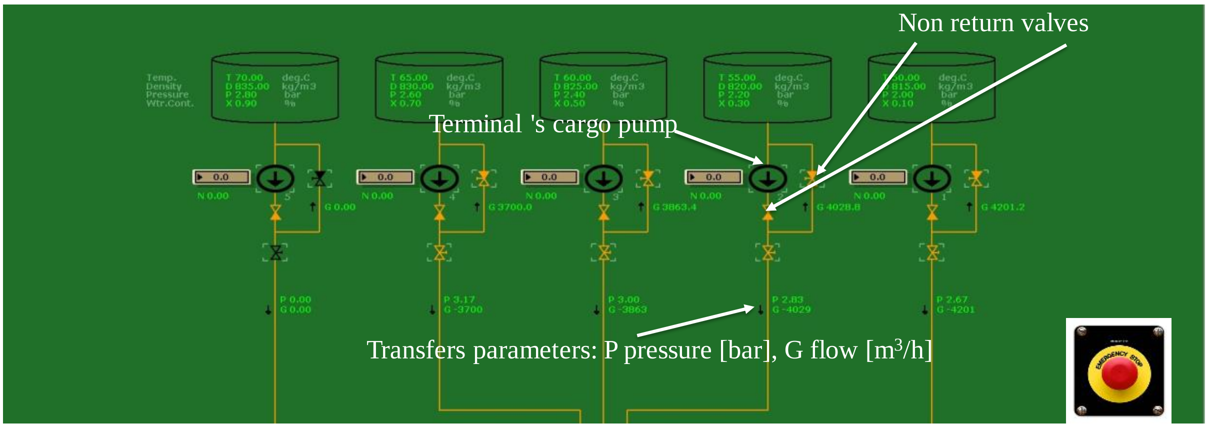

Figure 44. Shore cargo tanks and pipelines arrangement.

On crude oil tankers the relief valve (on by-pass line) between the cargo pump and discharging valve is used for protection the cargo system. Relief valves allowed drop down the pressure in the system to the cargo pump separator.

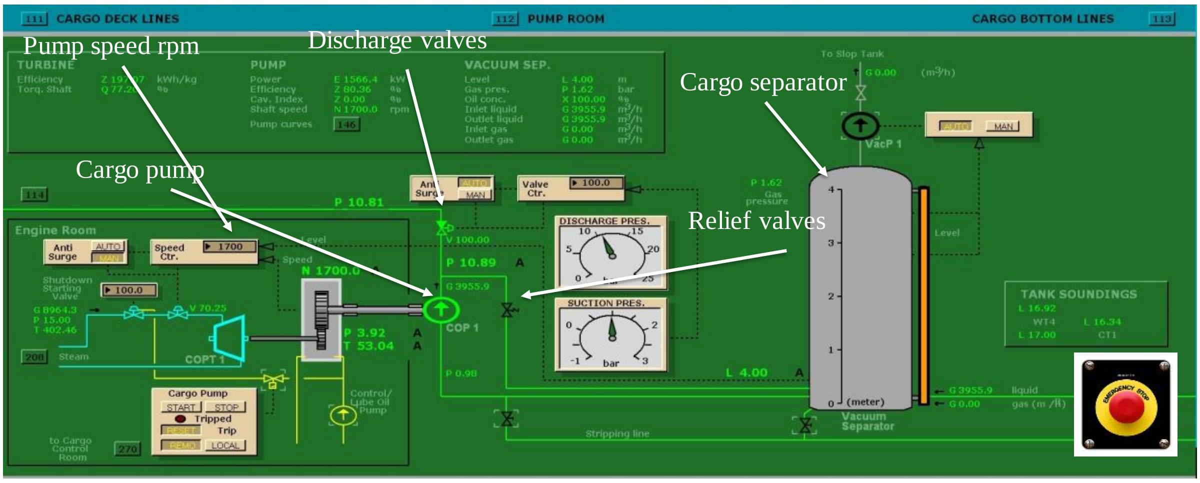

Figure 45. Centrifugal cargo pump arrangement with pressure relief and non-return valves.

Automatic activation of the system can also be related to the closing of automatic valves or the activation of other systems (fast opening fail-safe valve) that release pressure from the pipeline system, and the cargo should be directed to specially dedicated tanks.

8. Conclusion

The paper describes operations during oil transfer process in a terminal and associated with them threats and potential oil spill accidents. The reliability and availability analysis of crude oil transfer system in the oil port terminal is performed. Fault Tree Analysis (FTA) and various classifications of causes of oil spill accidents are proposed, which may help to identify and analyse potential causes and possible scenarios of oil spill incidents and accidents in the oil port terminal during oil transfer. Determining the causes of oil spill accidents and identification of potential spill sources can help to avoid or mitigate the effects of potential spills during oil transfer in a terminal in the future.

For the liquid cargo transfer some guidelines prepared by leading industry-related organisations exist. ISGOTT is a main and basic guide for safety procedures in oil terminals, as well as onboard the tankers. Presented in the paper Ship/Shore Safety Check List (SSSCL) helps to the involved parties to determine potential hazards and provide safety-checks. Emergency Shutdown System (ESD) – especially linked, is a critical tool to increase level of the safety during oil transfer between terminal and the vessel. There are few additional systems related or connected to the ESD like Emergency Release System (ERS) or surge relief.

Because the human factor is one of the major elements that can lead to the accident in the oil terminal, particular attention in the paper has been paid on solutions related to human factor. One of the best methods to increase the safety in human factor field is improvement of the skills by regular training. Utilization of LCHS (Liquid Cargo Handling Simulators) could increase the safety level by gaining experience of the trainees and improving their knowledge.

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Appendix A – Glossary

Barge. There is no universally recognised definition of a barge. Barges can be self-propelled, towed or pushed, and may be used to carry or store liquid hydrocarbons, chemicals or liquefied gases in bulk. They may be employed in inland waterways or at sea outside port limits.

Cargo transfer. Operation when crude oil, LPG or other hydrocarbon products are moved from a ship to a terminal, or vice versa, by means of pumping.

Emergency Release System (ERS). System for quickly and safely disconnecting a loading arm from a ship with minimal product spillage. It consists of an emergency release coupler between two interlocked block valves.

Emergency Shutdown (ESD) system. ESD systems execute a sequential shutdown of ship or terminal pumps and valves in an emergency. ESD systems shut down the cargo transfer operation in a quick and controlled manner by closing the shutdown valves and stopping the transfer pumps and other relevant equipment.

Flow rate. Linear velocity of flow of liquid in a pipeline, usually measured in metres per second (m/s). The determination of the flow rates at locations within cargo pipeline systems is essential when handling static accumulator cargoes.

Loading arm. Articulated metal loading arm system used for transferring product(s) to or from ships with the capability of accommodating differences in tides and freeboard and ship motions.

Manifold. Flanged pipe assembly onboard ship to which the presentation flange of the loading arm or spool piece connects.

Pendant ESD unit. Hand-held portable unit for controlling the ESD.

Powered Emergency Release Coupling (PERC). Emergency release coupling that uses stored energy to ensure breakout through any ice build-up.

Pressure surge. Sudden increase in the pressure of the liquid in a pipeline brought about by an abrupt change in flow rate.

Ship. Any vessel, including barges, that is designed to carry oil, liquefied gases or chemicals in bulk.

Ship blackout. Operating in the event of loss of power.

Terminal. Place where ships are berthed or moored for the purpose of loading or discharging hydrocarbon cargo.

Appendix B – Courses on the LCH Simulator

Twelve movies with instructions on how to deal with various possible situations that occurred during the oil transfer at the terminal.