Assurance of reliability and safety in liquid hydrocarbons marine transportation and storing

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Abstract. The problems of assurance of safety and reliability in the liquid hydrocarbons marine transportation and storing are described. The requirements of standard IEC61511 have to be fulfilled for the load/unload in tanker’s system under dynamic loads on the pipeline system. The safety zones for fires of the type “fireball” and the spillage have to be determined when storing the liquid hydrocarbons. An example of the achieved necessary safety level of the duplicated load system, the conditions of the pipelines reliable operation under dynamic loads, the principles of the method of the liquid hydrocarbons storage safety zones under possible accident conditions are represented.

1. Introduction
There are several main problems to ensure reliability and security of systems and components which are applied in processes of liquid hydrocarbons loading/unloading, transportation and storage.

Transportation and storage of liquid hydrocarbons such as oil and liquefied natural gas (LNG) are composed of consecutive processes of loading, piping, level control, unloading into storage, safe storage [1]. The port or deep sea is the usual working environment for oil and LNG tankers. The particular properties of liquid hydrocarbons stipulate necessity to increase safety requirements to the load/unload pipeline systems reliability and to determine safe zones around storages. It is necessary to apply the required standards, models and methods to estimate reliability and security for considered processes.

2. The security levels
Standard IEC61511 is used for the design of safety systems of the tanker including security of the transportation of LNG because there is no special safety standard in this area. Application of IEC61511 is justified by the following arguments: the operating procedure of the ship fluid systems is analogical to working procedures in other branches of production; IEC61511 is adopted in many areas in the EU, Russia, China and Japan [2, 3].

The security systems produced by most of major manufacturers also comply with this standard; that is why, implementation of four levels of security beginning with SIL1 and ending with SIL4 when designing load/unload systems for security of oil and LNG tankers is ensured by the confirmation to international standards.
The systems life cycle which is defined by standard IEC61511 includes process design, study and safety assessment allocation of safety function, system design, system integration, local installation, adjustment and verification, the input to the exploitation and maintenance of the system, system update.

The load system ensures safe operation, continuous operation and resistance to external influencing factors. The probability of efficiency loss of the main system elements is approximately $2.6 \times 10^{-3}$ for liquid level sensor, $4 \times 10^{-4}$ for emergency stop, $3.5 \times 10^{-3}$ for inlet valve, $9.4 \times 10^{-4}$ for self-leveling pump. Based on the analysis it is shown that the safety level of the emergency stop system corresponds to SIL3 and for load system the probability of loss of efficiency will be $7.4 \times 10^{-3}$. This value corresponds to levels SIL2 and SIL3 required to improve the system, to duplicate converter fluid level and to add input valve. In a redundant configuration, the probability of loss of efficiency will be $4.2 \times 10^{-4}$ so the safety integrity level SIL3 is reached. The processing and visualization modes are required after the start of the security system. It is necessary to assess the reliability of the most important elements with consideration of their operating conditions specific.

3. Evaluation of the reliability of steel pipelines

Such methods are known, however, it’s not fully taken into account the specifics of the dynamic random loads appearing during loading of a tanker with liquid hydrocarbons. The problem of dynamic reliability is harder than of the static one therefore the article considers the random character of loads for the subsequent reliability analysis. The changes in the load consider as a dynamic factor [4-7]. The model proposed in [8] applied to solve a problem of dynamic reliability evaluation for the practical cases. Application of the models of a random process and sudden random loading application allows one to simulate the strength degradation process, and to create a dynamic mathematical model of system components reliability. It is necessary to consider the time dependence of the load random variable and strength. It matters for more accurate analysis and reliability estimation as well as for ensuring secure operation of the system and making informed decisions in the operation.

Let us consider the equation for the limit state:

$$g(X) = r - \sigma,$$

where: $r$ – the strength of the material; $\sigma$ – stress; $X$ – a vector random variable.

The failure state is defined as $g(X) \leq 0$, the working state is defined as $g(X) > 0$. The proposed model for reliability analysis is used in circumstances where strength and tension slightly change depending on time. Strength and tension are considered as a random variable. The reliability coefficient can be obtained in accordance with the equation [9][10]

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{E[g(X)]}{\left(Var[g(X)]\right)^{1/2}},$$

where: $\mu_g$ and $\sigma_g$ – average and standard deviation functions of the state.

The influence of external factors and working environment, the degradation of strength and the change in accidental loads should be taken into account for loading/unloading system of liquids. The equation of state takes the following form if the strength and the stress are represented as random process [11, 12]:

$$g(X,t) = r(t) - \sigma(Y,t),$$

where: $r(t)$ is a random process of the strength degradation, $\sigma(Y,t)$ is a random process of loading, $Y$ is a vector random variable associated with the effect of the load.
Method [9] allows representing dynamic reliability coefficient and dynamic reliability as:

\[
\beta(t) = \frac{\mu_{g(t)}}{\sigma_{g(t)}} = \frac{E[g(X,t)]}{\sqrt{\text{Var}[g(X,t)]}},
\]

(4)

\[
R(t) = \phi(\beta(t)) = P\{r(t) > \sigma(Y,t)/t \in [0,t]\},
\]

(5)

Last formula defines the probability that the strength of the component at each moment of the life cycle is more than the load effect and it is in reliable condition.

Let us consider the external load components for the two cases.

In the first case, when the external load is constant and obeys a certain distribution, the average value and variation of load are not changed at each moment. They are represented by the same type of distribution; therefore, the function takes the form:

\[
g(X,t) = \min r(X,t) - \sigma.
\]

(6)

In the second case, when the load changes depending on time and could not described by the known distributions, the probability distribution function determination of a random variable of load could be obtained by the following model:

a) divide the base period \(T\) into \(n\) equal time intervals \(\tau\), i.e., \(\tau\) is equal to \(T/n\);

b) determine the probability distribution function \(F_{\tau}(x)\) of the maximum load value \(S_i\) on the interval \(\tau\) according to the sets of statistics;

c) assume that for each segment \(S_i\) are mutually independent and have the same distribution function \(F_{\tau}(x)\);

d) set distribution function of the maximum load \(S_i\) on sequential segments (the equivalent is a basic period \(T\)) on the basis of a distribution of extreme values of the maximum member of:

\[
F_{\tau}(x) = P\left(\max_{1 \leq i \leq n} S_i \leq x\right) P(S_1 \leq x) P(S_2 \leq x) ... P(S_n \leq x) = \prod_{i=1}^{n} P(S_i \leq x) = \left[F_{\tau}(x)\right]^n
\]

(7)

The definition of the distribution of \(n\) maximum of mutually independent random variables is a common operation in the theory of probability, but when the value of \(n\) is large enough, the determination of the distribution of maximum values and statistic parameters are complex, and here, in accordance with [9], the maximum distribution of random variables of several independent normal distributions is represented by a distribution of type I extreme value.

It is possible to transform the distribution function of equivalent loading at a random loading process, varying with time, so the calculation formula of reliability under the random loading process is:

\[
R(t) = P\{r > \max \sigma(Y,t)/t \in [0,T]\},
\]

(8)

where \(\max \sigma(Y,t)\) is the maximum equivalent load effect of the random loading process. This formula shows that when the strength on each segment of their service life \(T\) is greater than the strength of the components, the components of the pipeline could be in good condition.

In the event of a loss of the components strength it is necessary to consider the possibility of accidents for industrial facilities storage and transportation of liquid hydrocarbons to ensure the safety of personnel and environment.

4. The danger zone around the storage of liquid hydrocarbons
The danger zone around the potentially dangerous object is being built taking into account the expected average for the considered period of time the meteorological conditions. These conditions define the envelope boundary zones of the dangerous actions of the totality of the destructive factors in emergency situations (ES) on a given industrial object \[13\][14].

The destructive factors that are considered when building the danger zones are the thermal impact of fires; the action of the shock wave; the toxic effects of chemical substances; radioactive effect; mechanical effect of fragments and debris (elements) of structures and buildings. For each potentially hazardous object pre-defined data contain the parameters which characterize the possible development of ES for each destructive factor. A method of constructing a danger area for a given object includes the definition of partial zones of dangerous action for each amazing factor and their combination.

Let us consider the minimum permissible removal boundaries on thermal effects, which is defined as

\[
R_{\text{therm}}(\varphi) = \max \big\{ R_{\text{therm},h}(\varphi), R_{\text{therm},m}(\varphi) \big\},
\]

where \( R_{\text{therm},h}(\varphi), R_{\text{therm},m}(\varphi) \) - the minimum permissible removing the boundary from the centre of the object in the direction specified by the polar angle \( \varphi \), at the critical thermal stress on humans (service and production personnel) and machines (vehicles), respectively.

The minimum permissible removal of a dangerous zone at the critical level of heat exposure for personnel and the vehicle are calculated from the condition not exceeding the specified degree of destruction of people and the specified degree of heating the fuel tanks of vehicles in case of fire. Formalized representation of these terms varies depending on the type of fire. The following types of fire are identified: the spillage; the type of "ball of fire"; the burning of buildings and industrial facilities.

The condition not to exceed the expected probability of destruction from the action of the thermal impact above the preset maximum permissible threshold value is defined. This condition is considered for the fire type "spillage" and "fireball" for determining safe distance from the centre of the fire, the defeat of the personnel. It is assumed for calculations that the thermal radiation source is located in the centre of the considered object. The distance from the radiation source in this case is measured by the value of the radius-vector in the adopted polar coordinate system; \( \tau \) - time of heat flow impaction for person. The time of the burn-burning substances was adopted as this value for the calculations. The definition condition of the boundary of dangerous area for vehicles and special equipment for types of fire (spillage and "fireball") takes the form:

\[
q(R, \varphi) \leq q^\sigma ,
\]

where \( q(R, \varphi) \) is the heat flux density at a given distance from the centre of object \( R \), and in the direction specified by the polar angle \( \varphi \); \( q^\sigma \) - critical heat-flux density of the incident radiation.

For the fire type "fireball" method of determining the values of heat flow is different. Fire "fire ball" is a large-scale diffusion combustion pair-gas-air cloud realized with the depressurization of the tank of flammable liquid or gas under pressure. The density of the heat flux incident from the surface of "fireball" on the elementary platform is equal to:

\[
q = q^\tau e^{-7.0 \times 10^{-4} \sqrt{R^2 + \left(D^\text{eff}/2\right)^2}} \cdot \varphi, \quad D^\text{eff} = 5.33 \cdot M^{0.327}, \quad \varphi = \frac{1}{4 \cdot \left[ 1 + \left( \frac{R}{D^\text{eff}} \right)^2 \right]^{0.5}},
\]
where \( q^d \) is the density of the heat flow self-radiation "fireball"; \( \varphi \) is angular radiation coefficient "fireball" on the elementary area of the irradiated surface; \( R \) is the distance from the point on the earth's surface directly under the centre of the "fireball" to the irradiated object; \( D^{eff} \) is the effective diameter of the "fireball"; \( M \) is the mass of combustible material.

The value of the removal of the boundaries of the affected area of the vehicles in the event of fire “spillage” and "fireball" is calculated as

\[
R_{\text{fireball}}^\text{veh} (\phi) = \arg \left( q(R,\phi) \leq q^c \right),
\]

where \( q(R,\phi) \) is the heat flux density incident on the elementary area at the distance \( R \) from the centre of fire in the direction specified by the polar angle \( \phi \).

5. Conclusion.
The authors did not aim to cover all the objects and details of the life cycle of liquid hydrocarbons transportation and storage. However the problems of security and reliability assurance are urgent especially for the processes of loading/unloading and storage. The models and methods can be considered together with task performance processes and environmental protection, but it is beyond the scope of this article.

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