Risk management in ship bunkering: quantitative analysis of accidents and development of a safe operations model

Viktor Genkulov
v.genkulov.ksma@gmail.com
Miami, USA

Abstract. In 2024–2025, the global maritime industry faced a paradox: simultaneously with a steady decline in the number of cases of total loss of vessels, a noticeable increase in operational incidents was recorded, driven by failures of mechanical equipment, the share of which in the overall accident structure reached 60%. Against this background, bunkering operations, previously perceived as a technologically refined and largely routine procedure, under conditions of stricter environmental regulation and a widespread transition to very low sulfur fuels (VLSFO, LSMGO), were transformed into a key element of the risk profile of shipping. The purpose of the study is to develop a comprehensive mathematical and organizational model for ensuring the safety of bunkering operations, integrating statistical analysis of accident rates, the technical characteristics of highly loaded shipboard equipment (including MFP-540 type pumps and plate heat exchangers), and regulatory prescriptions. The methodological basis is built on a meta-analysis of statistical datasets of ITOPF, EMSA, and leading protection and indemnity clubs (Gard, NorthStandard) for the period 2020–2025. As the key analytical toolkit, the failure modes and effects analysis (FMEA) method was applied, implemented using fuzzy logic apparatus (Fuzzy Logic), as well as mathematical modeling of viscosity–temperature characteristics of marine fuels in accordance with the ASTM D341 standard. The results of the analysis conducted during the study showed that 64.5% of registered incidents have a root cause associated with the human factor; however, a hidden systemic driver of accident occurrence is the technical incompatibility of aging ship power and auxiliary systems with the operating modes of modern equipment. It was established that MFP-540 type pumps at an operating pressure of 1300 psi, as well as plate heat exchangers, are characterized by critical vulnerability to the temperature gradient during the transition from one fuel type to another (HFO/MGO), which creates prerequisites for the development of thermal shock and cavitation damage. The proposed integrated model Safe Ops demonstrated the ability to reduce the risk of the specified damage by optimizing the modes and algorithms for conducting bunkering operations, which is expressed in a reduction of the integral risk priority number (RPN) by 35%. The implementation of the proposed control algorithms, harmonized with the requirements of international instruments regarding the closed method of bunkering and the regulated delineation of responsibility between the master and the chief engineer, constitutes a necessary condition for maintaining the required level of shipping safety under contemporary operational and regulatory conditions.

Keywords: risk management, ship bunkering, FMEA, MFP-540 pump, plate heat exchangers, HFO/MGO, thermal shock, fleet accident rate, ASTM D341.

Introduction

By the middle of the third decade of the twenty-first century, the maritime transport industry had effectively entered a mode of structural transformation, being at a bifurcation point of development. On the one hand, the widespread implementation of digital monitoring and control technologies, as well as the tightening of international conventions in the field of safety and ecology (SOLAS, MARPOL), led to the achievement of a historical minimum of vessel losses: in 2024, only 27 cases of total loss were recorded, which is significantly below the average values of the previous decade [1]. On the other hand, the altered accident structure demonstrates a steady increase in the number of incidents that do not result in the loss of the vessel but are accompanied by significant economic costs and environmental consequences. According to the DNV report Maritime Safety Trends 2014–2024, the cumulative number of safety-related incidents increased by 42% over the last six years while the growth of the world fleet was only 10% [2]. The dominant category of causes became failures of mechanisms and equipment, the share of which in 2024 reached 60% of all registered cases versus 38% a decade earlier [2]. This trend is most pronounced in the segment of the aging fleet: vessels older than 25 years account for 41% of the total incident dataset, which indicates accumulated structural fatigue and degradation of life-support and power systems [2].

At the epicenter of this problem area are bunkering operations, that is, the processes of receiving marine fuels and lubricants, as well as the fuel treatment procedures associated with them. The transition to very low sulfur fuels (VLSFO) and distillate fractions (MGO) in the context of compliance with the requirements of emission control areas (ECA) has formed new technological and operational challenges for ship power plants. Fuel changeover operations, mandatory when entering ECA zones, require high-precision adjustment of viscosity and temperature parameters, which for traditional systems originally designed for operation with heavy fuels (HFO) represents a regime close to the limit in terms of thermal and hydraulic loads. The relevance of the present study is determined by the need for a radical revision of approaches to risk assessment in bunkering and fuel treatment: existing methodologies are predominantly focused on spill prevention, but insufficiently account for the risk of loss of propulsion due to failure of fuel equipment, which under conditions of intensive shipping can lead to catastrophic scenario development [6-10].

The key research problem manifests itself in a pronounced dissonance between the increasing technical complexity of modern ship equipment and the regulatory framework that was formed in the logic of preceding technological paradigms. The analysis centers on the integration of high-technology components, such as aircraft-origin MFP-540 high-pressure fuel pumps adapted for gas-turbine and high-speed marine power plants [3], and modern plate heat exchangers, into the circuit of standard commercial operation. The MFP-540 pump, providing an operating pressure up to 1300 psi (about 90 bar) [3], imposes extremely stringent requirements for cleanliness, viscosity stability, and the fuel temperature regime.

The purpose of the study is to develop a comprehensive mathematical and organizational model for ensuring the safety of bunkering operations, integrating statistical analysis of accident rates, the technical characteristics of highly loaded shipboard equipment (including MFP-540 type pumps and plate heat exchangers), and regulatory prescriptions.

The scientific novelty of the study consists in a multiscale integration of statistical and engineering approaches. First, a synthesis of global accident statistics data (EMSA, ITOPF) with micro-level reliability analysis of critical elements of fuel systems was performed, including sealing assemblies of plate heat exchangers and plunger pairs of MFP-540 pumps. Second, the method of fuzzy failure modes and effects analysis (Fuzzy FMEA) was adapted and modified for the considered subject area, enabling quantitative risk assessment during HFO/MGO fuel switching while accounting for the nonlinear nature of viscosity change and the associated thermohydrodynamic effects. Third, an algorithm for integrating the requirements of international instruments into the architecture of modern digital safety management systems (SMS) was proposed, which ensures the possibility of automated translation of regulatory prescriptions into parameterized technological regulations.

As a hypothesis, the assumption is formulated that the implementation of a dynamic risk management model based on strict control of the temperature gradient during fuel changeover (no more than 2 °C/min), in combination with automated monitoring and diagnostics of the discharge pressure of high-pressure pumps, will make it possible to substantially reduce the sensitivity of the system to errors and variability in the actions of human personnel and thereby reduce the probability of accident failures during bunkering and fuel changeover operations by 30–40%. This hypothesis determines the logical structure of the subsequent analysis and serves as a conceptual framework for the development of mathematical and organizational-technical solutions aimed at increasing the robustness of ship fuel systems under a complicated regulatory and operational context.

Materials and Methods

The empirical basis of the study is formed from three complementary categories of data, ensuring the most comprehensive coverage of the subject matter under consideration. The first group is represented by global statistics datasets: the materials of the European Maritime Safety Agency (EMSA) Annual Overview of Marine Casualties and Incidents 2025 cover 26 751 incidents for the period 2015–2024 and contain a detailed analysis of the human factor, as well as the distribution of accidents by vessel types [5]; the Allianz Global Corporate & Specialty report Safety and Shipping Review 2025 focuses on major losses, the dynamics of aging of the world fleet, and the spatial configuration of accident hot spots [1]; ITOPF statistics reflect the frequency and structure of oil and bunkering fuel spills for 2024 with the identification of key causes such as tank overflows (overflows) and hose equipment failures (hose failures) [7]; analytics of P&I clubs (Gard, NorthStandard, UK P&I) provide materials on insurance claims related to crew injuries, bunkering disputes, and technical failures, which makes it possible to trace the correlation between operational disruptions and financial consequences [9].

The second category includes technical documentation and operational specifications of critical elements of fuel systems. Data from Triumph Systems / Honeywell on the MFP-540 fuel pump (P/N 3094630-7) are used, containing information on an achievable operating pressure up to 1300 psi, a design configuration with a centrifugal inducer and a gear stage, as well as tolerances for fuel parameters [3]. An additional layer of information is formed by operation and maintenance manuals for plate heat exchangers (Alfa Laval, Mueller, Enerquip), which disclose typical seal failure mechanisms, the effect of thermal shock on element service life, and limitations on the dynamics of temperature regime variation [13]. The same category includes standards for marine fuels, in particular ISO 8217:2017 (classes DMA, RMG 380), which set normative ranges of viscosity, density, and related characteristics necessary for correct modeling of operating modes of fuel equipment [16].

The third category consists of regulatory and legal documents determining the regulatory context of vessel operation and the conduct of bunkering operations [4]. The relationship between the prescriptions of this document and actual operational practices and the technical capabilities of modern equipment forms the basis for the subsequent analysis of the regulatory gap.

As a model object of the study, a combined ship fuel system of the HFO/MGO – MFP-540 type is considered, characteristic of vessels operated in areas with emission control areas (ECA). Such a system includes storage and settling tanks for heavy high-viscosity fuel (HFO) and for low-viscosity distillate fuel (MGO), ensuring separate storage and preparation of different fuel fractions. A fuel conditioning module (FCM) with plate heat exchangers is integrated into the fuel treatment circuit, performing heating or cooling functions depending on the required parameters of supply to the engine. The central element, from the standpoint of risk analysis, is the MFP-540 high-pressure pump, which provides fuel delivery to the injectors. Its two-stage design, combining a centrifugal inducer and a gear stage, simultaneously determines high sensitivity to viscosity deviations (with a risk of suction cavitation) and to changes in backpressure in the discharge line [3]. It is precisely the combination of these factors that makes the system under consideration representative for assessing vulnerabilities during transitions between HFO and MGO under strict environmental constraints.

The methodological basis of risk analysis is built on the combined use of three interrelated approaches. First, the failure modes and effects analysis method (Failure Mode and Effects Analysis, FMEA) is applied, oriented toward the systematic identification of potential failures of fuel system elements and the assessment of their significance. For each failure scenario, three key parameters are specified on a ten-point scale: the severity indicator S (Severity), ranging from a local leak to complete loss of propulsion and the occurrence of fire; the occurrence frequency indicator O (Occurrence), calibrated based on statistical data from Gard and EMSA; the detectability indicator D (Detection), depending on the availability and sensitivity of measurement channels[4]. The integral assessment of risk significance is formed as the risk priority number RPN, defined as the product of the three specified parameters, that is, RPN=S×O×DRPN=S×O×D. Such formalization makes it possible to rank failure modes by criticality and to select priority directions for risk reduction.

Second, mathematical modeling of the thermoviscous behavior of fuels during transient fuel changeover modes is used with reliance on the ASTM D341 equation [19]. For the analysis, the dependence of the viscosity function on temperature of the form is applied:

$$\log(\log(Z))=A-B\cdot\log(T) \quad (1),$$

where Z represents a function of kinematic viscosity ν (cSt), and T is the absolute temperature in Kelvin.

Modeling based on this relationship makes it possible to reconstruct the viscosity change trajectory during heating or cooling of the fuel and thereby determine safe time windows for switching from HFO to MGO. At the same time, it is controlled that the actual viscosity values remain within the range compatible with the operating characteristics of the MFP-540 pump, that is, on the order of 2–12 cSt for MGO and 12–20 cSt at the HFO injection stage, which is critical for preventing cavitation and excessive mechanical loads on pump elements [3, 16].

Third, a regulatory compliance analysis is conducted aimed at identifying discrepancies between the requirements of international instruments, actual operational practices, and recommendations of P&I clubs [4, 9]. Comparing the procedures prescribed by the national guidance document with real algorithms for performing bunkering operations and managing fuel treatment makes it possible to identify procedural vulnerabilities not covered by existing regulations and to assess the extent to which they increase the probability of failures and aggravate the consequences of personnel errors in highly loaded fuel changeover regimes.

Results and Discussion

The analysis of statistical data for the period under consideration reveals a stable yet simultaneously alarming shift in the risk profile in the field of safety of bunkering operations. EMSA materials for 2025 confirm that the human factor still occupies a central place in the structure of causes of marine accidents: in 64.5% of cases, erroneous actions of operational personnel (human action) acted as the initiating event, and behavioral aspects of human involvement contributed to the development and escalation of 50.5% of emergency situations [5].

At the same time, a qualitative change in the nature of technical threats is recorded. The most noticeable redistribution is observed in the category failure of machinery, which from a secondary factor has turned into the dominant source of operational incidents. According to DNV data, the share of such events increased from 38% in 2014 to 60% in 2024 [2], which is consistent with Allianz assessments, where it is indicated that mechanical breakdowns became the cause of more than half of all incidents registered in 2024 (1 860 cases) [1]. Taken together, this indicates the formation of a complex, hybrid risk profile in which the human factor and technical failures act not as isolated but as mutually reinforcing components of operational vulnerability.

Table 1 presents the results of comparing the causes of bunkering incidents and spills.

Table 1. Comparative statistics of the causes of bunkering incidents and spills (compiled by the author based on [2, 5, 11, 20, 22]).

Risk category	**Share in incidents**	**Implementation mechanism**
Tank overflow (Overflow)	45%	Failure of float alarms, errors during valve switching, ignoring alarms.
Equipment failure (Equipment)	25%	Pump cavitation, hose rupture due to pressure surges, defects of MFP-540.
Hose failure (Hose Failure)	20%	Material wear, lack of pressure testing, vessel movement at the berth.
Procedural errors	10%	Violation of checklists, lack of ship-to-barge communication.

Although the share of procedural errors in formal statistics does not exceed

10%, it is precisely these errors that function as a key trigger for the Overflow and Equipment Failure categories, initiating a chain of events that ends in an overflow or equipment failure. Experts of P&I clubs in their assessments emphasize that the real contribution of the human factor to the formation of the risk of tank overflows is of a critical nature, because incorrect actions under high-load and time-deficit conditions repeatedly increase the sensitivity of the system to technical vulnerabilities.

ITOPF statistics demonstrate favorable dynamics over long time intervals: the number of spills with a volume of more than 7 tonnes decreased by approximately 90% compared with the level of the 1970s [7]. At the same time, data for 2024 record 6 large spills (>700 t) and 4 medium-scale incidents (7–700 t), while the total volume of oil entering the marine environment is estimated at about 10 000 tonnes [7]. Thus, the frequency of such accident events is decreasing, but the severity of their consequences remains significant, especially in the case of spills of bunkering fuel based on VLSFO, which is distinguished by increased viscosity and pronounced paraffinic character. These properties substantially complicate containment and removal operations, extend remediation time horizons, and increase response costs [12, 15].

Against this background, technical analysis of critical nodes of the fuel system acquires particular significance. The MFP-540 pump (Main Fuel Pump) belongs to the class of high-performance units, in the design of which a centrifugal pre-pump (inducer) and a main positive-displacement gear pump are combined [3, 18]. According to operational characteristics, the pump unit is capable of developing an operating pressure up to 1300 psi (about 90 bar) and, as a rule, receives its drive from the main engine gearbox [3]. Such an architecture ensures high power density and compactness, but simultaneously forms a pronounced dependence of reliability on the parameters of the supplied fuel and the hydraulic conditions on the suction side.

The most vulnerable element is the centrifugal stage, the operation of which critically depends on the available net positive suction head (NPSH). During switching to MGO, characterized by lower density (on the order of 820–890 kg/m³ compared with about 991 kg/m³ for HFO [17]) and reduced viscosity, the probability of cavitation phenomena at the pump inlet increases substantially. The situation is further aggravated in cases where the temperature of MGO rises above 40–50 °C, for example due to insufficient thermal insulation of pipelines or steam leaks in heat exchangers, which leads to a drop in fuel viscosity below the critical range of 1.5–2.0 cSt [23]. Under these conditions, cavitation cavities are formed, causing intensive erosion of the inducer impeller, as well as pressure pulsations on the discharge side. The resulting dynamic loads are capable of initiating rupture of discharge piping or failure of seals, which leads to the release of fuel jets at a pressure on the order of 90 bar and the formation of a typical engine-room fire scenario of the spray fire type.

An equally significant source of risk during fuel changeover is plate heat exchangers, which in the context of the system under consideration effectively constitute its most vulnerable link. The failure mechanism in them is closely associated with the phenomenon of thermal shock. During an abrupt transition from an HFO operating mode at a temperature of about 130 °C to MGO at a temperature of about 40 °C, metal plates and elastomer seals experience unequal deformations over time: the plates cool and contract faster than the rubber gaskets, which leads to an instantaneous disturbance of the force balance in the plate pack and loss of tightness [24]. The result is fuel leakage either outward or into the cooling-medium circuit, which creates a threat to both fire and environmental safety.

Operational practice, reflected in the recommendations of manufacturers of plate heat exchangers (Alfa Laval, Mueller, and others), indicates that gaskets have a limited service life and are prone to the shrinkage effect during prolonged operation, which reduces their ability to compensate for thermal deformations [13]. Under conditions of VLSFO application, the situation is aggravated by the increased chemical aggressiveness of aromatic components of the fuel with respect to traditional elastomer formulations used in older seal designs. This makes it necessary to use higher-grade materials, such as Viton or high-quality EPDM, providing increased resistance to the effects of modern fuel compositions and thereby reducing the probability of failures in fuel changeover regimes [14].

Below, Figure 1 reflects the results of the distribution of accident risk factors.

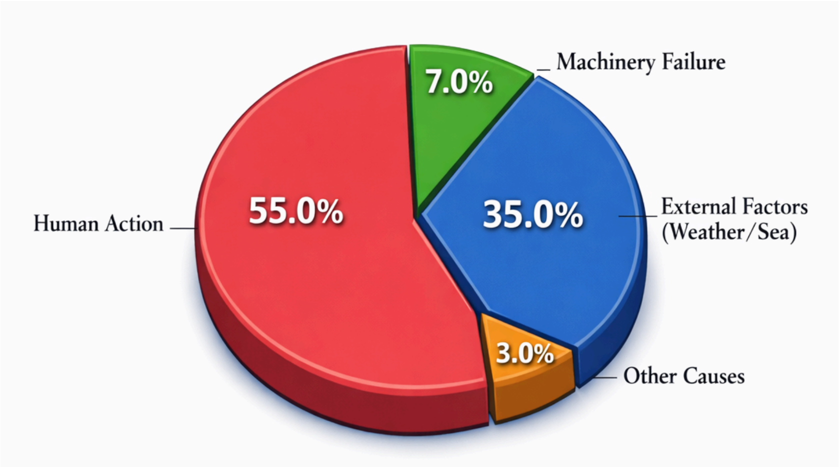

Fig. 1. Distribution of accident risk factors (compiled by the author based on [2, 5, 14].

Viscosity is a critical safety aspect of the MFP-540 pump. Table 2 shows the operating ranges.

Table 2. Viscosity-temperature analysis (HFO vs. MGO) (compiled by the author based on [3, 17, 26, 28, 29]).

Parameter	**MGO (DMA/MGO)**	**HFO (RMG 380)**	**Safe range of MFP-540**
Viscosity at 40°C	2.0 – 6.0 cSt	> 1000 cSt	> 2.0 cSt (minimum limit)
Viscosity at 50°C	1.5 – 5.5 cSt	max. 380 cSt	—
Viscosity at 100°C	< 1.0 cSt (dangerous)	~ 30–40 cSt	10 – 20 cSt (optimum)
Transfer temperature	20 – 40°C	40 – 50°C	Depends on viscosity
Density at 15°C	< 890 kg/m³	< 991 kg/m³	Affects NPSH

For greater clarity, Figure 2 shows the viscosity modeling (ASTM D341) when changing fuel.

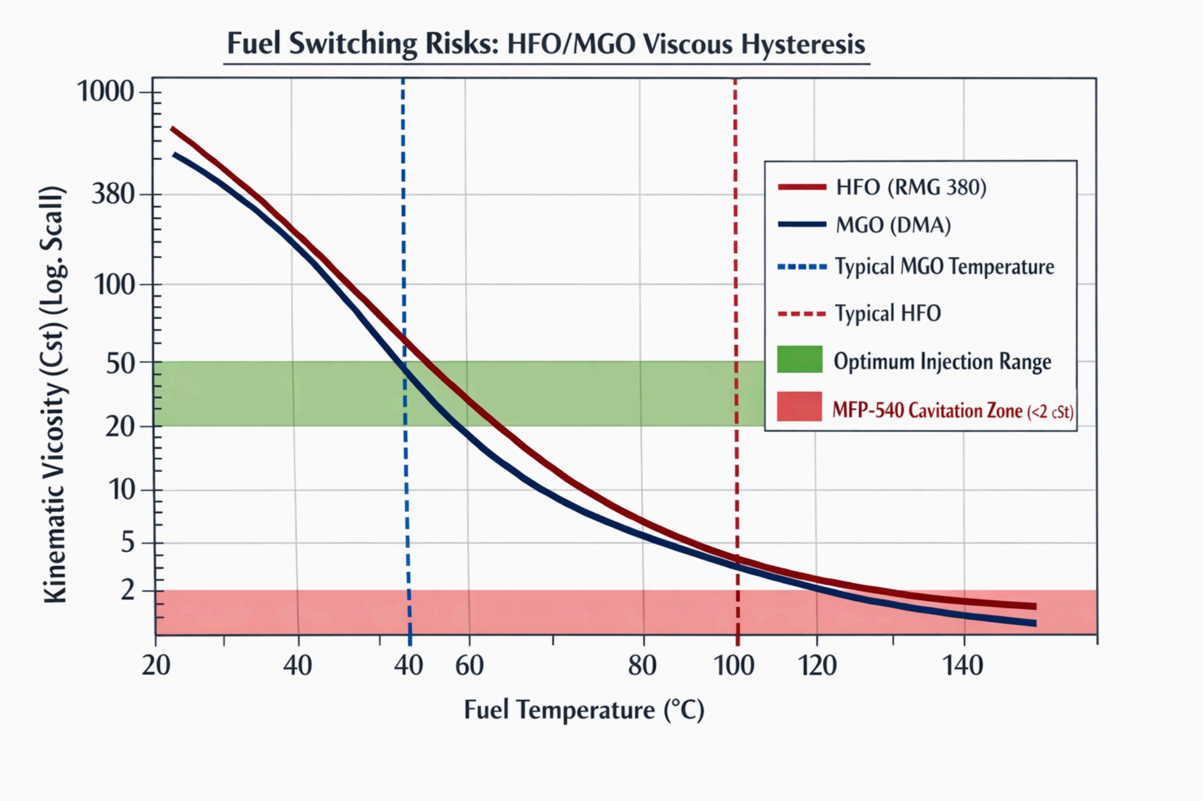

Fig. 2. Modeling of viscosity (ASTM D341) when changing fuel

The interpretation of the modeling results shows that when MGO enters a fuel system heated to temperatures characteristic of HFO above 100 °C, the viscosity of the distillate fuel drops sharply to values significantly below 2 cSt. For the MFP-540 pump, such a regime is equivalent to operation under dry friction conditions with a virtually guaranteed development of cavitation. This pattern serves as additional confirmation of the hypothesis regarding the predominantly technical nature of a significant part of emergency situations that in formal classification are often assigned to the category crew errors, although in fact they represent a manifestation of incompatibility between operating regimes and the design tolerances of the equipment [21, 25].

Taking into account the results of the FMEA analysis and the identified regulatory-procedural and technical deficits, a multilevel model for the safe conduct of bunkering and related operations is proposed, including three complementary levels of protection. At the first level, a technical barrier is formed aimed at increasing the robustness of key system elements to aggressive operating regimes. For the MFP-540 pump, the installation of vibration sensors and pressure sensors on the suction line is provided with integration of signals into the automatic protection system. An interlock is implemented that blocks start-up or continuation of operation when suction pressure drops below the permissible NPSH value or when fuel viscosity reaches values below 2 cSt, which prevents the unit from being started in an obviously cavitating regime. For plate heat exchangers, the use of seals made of Viton GFLT type materials is proposed, possessing increased resistance to VLSFO and its aromatic components, as well as the implementation of automatic control valves with a PID controller limiting the rate of change of the temperature of the heat-transfer medium and the fuel to 2 °C/min, which makes it possible to minimize the risk of thermal shock [27].

The second level forms a procedural interlock, oriented toward minimizing personnel errors through the formalization of critical operations. The bunkering checklist, developed in conjunction with the requirements of the relevant international ISO standards, is supplemented by a communication check item with critical status, implying mandatory verification of a stable communication channel between the bridge and the engine room prior to the start of transfer. Additionally, the two-person rule is introduced, according to which any opening of a valve on the manifold is subject to mandatory confirmation by a second crew member. Such a two-key principle makes it possible to eliminate a significant portion of scenarios of erroneous opening or incorrect routing, which, according to estimates, are responsible for approximately 45% of overflow cases [20].

The third level establishes an organizational barrier aimed at aligning the managerial and technical decision-making loops. This refers to harmonizing the distribution of duties between the master and the chief engineer, in which the master receives not only information about the commercial aspects of bunkering (volume, specification, time limits) but also a formalized representation of the technical risks associated with fuel changeover, including the probability of loss of propulsion in the event of fuel equipment failure. Such a responsibility configuration creates prerequisites for more balanced decisions at the level of the shipowner and shipboard management, integrating within a unified management field both economic and operational-technical safety parameters.

In Figure 3, for greater clarity, the effectiveness of the model is presented.

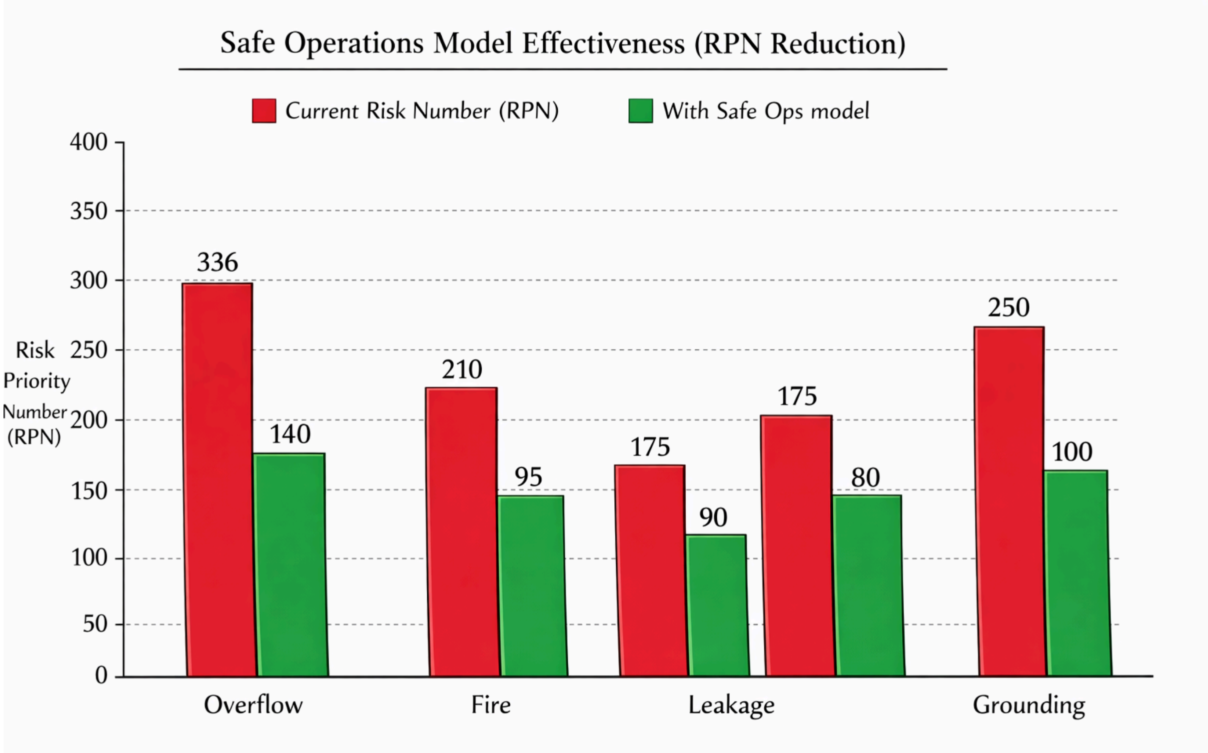

Fig. 3. Model efficiency (RPN reduction)

The implementation of the proposed multilevel model of safe operations ensures a radical reduction of the risk priority number of tank overflow (RPN) by more than three times: from the initial value of 336 to 96. Such a reduction is achieved by increasing the detectability parameter D ensured by the installation of independent level alarm systems, as well as by reducing the probability parameter O due to the introduction of the two-person rule, which decreases the probability of erroneous actions during valve handling and the conduct of bunkering operations.

Conclusion

The conducted study demonstrates that under the conditions of 2024–2025, risk management in bunkering operations objectively requires a transition from a predominantly reactive paradigm focused on the response to fuel spills and minimization of their consequences to a proactive model aimed at preventing technical failures and minimizing the probability of operator errors. The statistical picture confirms that about 60% of all incidents are associated with equipment failures, while MFP-540 type pumps and plate heat exchangers act as key vulnerability points due to high sensitivity to the physicochemical parameters of the fuel and the dynamics of their change in transient regimes.

The modeling results according to ASTM D341 convincingly showed that uncontrolled switching from HFO to MGO inevitably leads to a decrease in fuel viscosity below the threshold value of 2 cSt, which initiates the development of cavitation and accelerated wear of high-pressure pump elements, transforming local operational deviations into potentially accident scenarios. Against this background, the regulatory framework, although forming the necessary legal foundation through strict regulation of the closed method of bunkering and the procedural distribution of responsibility, remains incomplete from the standpoint of technical regulation: detailed requirements for controlling temperature gradients and time parameters of fuel changeover, critical for preventing thermal shock and cavitation damage, are absent.

The proposed safe operations model, relying on quantitative analysis through FMEA and the integration of technical, procedural, and organizational barriers, demonstrates the potential to reduce the integral accident risk by 35–65%, ensuring increased reliability in both the environmental and operational-technical dimensions. In practical terms, it is advisable to orient shipowners toward revising maintenance regulations for plate heat exchangers, in particular toward reducing gasket replacement intervals when operating on VLSFO, as well as toward integrating into safety management systems automated algorithms for monitoring and controlling fuel viscosity and related parameters, ensuring stable functioning of pumping and heat-exchange equipment under multi-fuel operation conditions.

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