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CONDITIONS FOR A RISK-BASED NAVAL SHIP SURVIVABILITY APPROACH: A STUDY ON FIRE RISK ANALYSIS

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ABSTRACT

In military operations, balancing risk is central, and a desire to entirely avoid risk may affect the potential for achieving military goals. Therefore, risk is an important aspect for understanding the operational conditions. This study discusses the assessment of operational risk to support ship design decisions.

Fire is a common consequence of weapon hits and is currently estimated to cause of 80 percent of naval ship loss. The purpose of this study is to describe and investigate the conditions for a risk-based approach to ship fire survivability, that can link probabilistic survivability theory and survivability measure selection. The aim is to suggest key aspects for a risk-based methodology.

To aid in the analysis, this study proposes cause and effect models for the fire risk analysis and describes the fire risk contribution from different types of ignition. The analysis shows that the reliability and validity of identifying potential fires depends on a qualitative and outward-focused analysis of the ships' intended operation, and the reliability and validity of the analysis on fire consequences depends on the specific data and descriptions used. For example, the magnitude of the fire risk can drastically change due to the operational choices (or unclear operational conditions).

This study concludes that the analysis requires understanding of the operational conditions. Subsequently, civilian risk-based approaches to fire risk are too limited because the approaches do not include aspects of the ship design and intended operation. Further, normal military vulnerability tools lack this ability. However, based on a stringent fire ignition analysis, including a definition of the intended operation, the ship design concept and the threats, civilian methods and tools can be used to assess the consequences.

Keywords: risk-based, naval ship design, littoral, small warship, survivability, fire, construction material

INTRODUCTION

Casualties, deliberate or accidental, are a reality in military operations, and the desire to fully avoid casualties may dramatically affect the potential for achieving military goals. It is impossible to prevent ships from being hit [1]; however, for the current asymmetric conflicts, there is a drive for higher efficiency and lower loss; thus, survivability is the focus. For survivability, risk must be balanced, and a comprehensive risk assessment process is essential for guiding risk management decision-making and prioritization [2, 3].

Risk is an important aspect of understanding operational conditions [3]. However, in guidelines such as The Naval Ship Code [4] and the Survivability of Small Warships and Auxiliary Naval Vessels [5], ship safety and ship survivability goals are discussed without introducing methods and tools to support design decisions. Therefore, an integrated approach is necessary to assess survivability and safety for naval ship design processes [6], which, if it is probabilistic, may be connected with survivability theory and the risk-based framework of military planning and force protection [7].

For naval ships, risk can be discussed from several different perspectives; this study discusses assessing operational risk to support ship design decisions. Herein, risk is defined as a function of the probability that an unwanted event will occur and its consequences. Risk analysis is used to investigate the consequences of identified hazards and estimate their probabilities. For such analyses, low-level factors, such as engineering specifications, system schematics and measured or estimated probabilities for areas such as threats or crew actions, are linked to the probability of the identified consequences. Risk analysis results must always be weighed against both risk tolerability levels and other operational parameters, such as possible operational gain, requested reliability and financial considerations. Generally, higher risks are tolerable if the potential operational gain is high [2, 8, 9].

Risk-based approaches for ship design have been developed using the term ‘risk-based ship design’, which is a more extensive framework than current developments by the International Maritime Organization (IMO) [10-12]. The focus for risk-based ship design is developing risk-management models for the intended ship operations. The models are then used with other knowledge models during the ship design process in accordance with Figure 1. Risk-based ship design can use both the explicit risk criteria developed by the IMO and the concept of safety equivalence [13, 14].

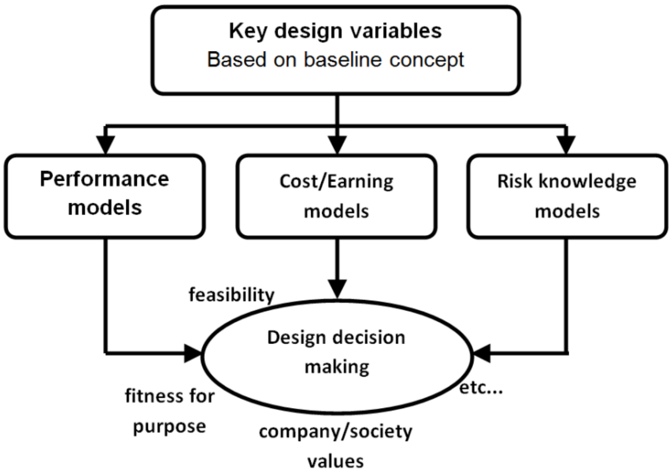

Figure 1. Design decision making in risk-based ship design. Redrawn from Vassalos [14].

Based on the need for a decision support approach for survivability design as well as development of civilian risk-based methods and tools, it can be assumed that risk-based approaches can be fully implemented in naval ship design (see, for example, the risk-based approach to naval ship damage stability proposed by Boulougouris and Papanikolaou [15]). However, without investigation, it cannot be assumed that such an approach includes the specific incident causalities for antagonistic threats [16, 17]. Therefore, the purpose of this study is to investigate the conditions for a risk-based approach to ship fire survivability (i.e., the conditions for a military-specific fire-risk knowledge model as defined by Figure 1). The aspects discussed are limited to fire survivability and exemplified through a quantitative example, wherein different design concepts for small warships under littoral conditions are compared. The focus is fire and design concepts, such as material choice, because both aspects are important and have an impact on the operation of the ship [18, 19]; therefore, these aspects cannot be analyzed based only on a traditional ship design perspective. The focus is also on fire because erroneous assumptions on the causes and effects of fires on naval vessels have been reported, especially in relation to construction materials [19, 20]. These reports demonstrate a need for a rational decision support process to prevent these assumptions from affecting future design choices.

This study proposes generic, top-level cause and effect models to describe fire risk analysis and describe the fire risk contribution from different types of ignition using a quantitative littoral example. Based on the proposed cause and effect models as well as the littoral example, this study analyzes the conditions for a risk-based approach. The aim of this analysis is to suggest the key aspects necessary to ensure reliability and validity for a risk-based methodology.

First, this study describes naval ship survivability and the key aspects of fires on naval vessels to serve as a theoretical framework. Thereafter, the critical theoretical and methodological points of the analysis on fire probability and consequences are described and exemplified using a quantitative example. In the section *Conditions for a Risk-Based Approach to Naval Ship Recoverability*, the fire risk for the vessel in the quantitative example is calculated and used to analyze how the critical points of the different analysis steps interact to form the conditions for analyzing naval ship fire risks. Finally, the results are discussed, and the conclusions are stated.

NAVAL SHIP SURVIVABILITY

It is no longer possible to consider vulnerability and recoverability as constants and assume that a hit equals a ship kill [1, 15, 21-23]. Currently, conflicts often occur in coastal areas, wherein threats are more difficult to detect and avoid due to short reaction times that increase the focus on vulnerability and recoverability [1]. These aspects are especially challenging for small war ships [5].

To meet the new challenges of current warfare, including asymmetric and littoral warfare, survivability must be examined more closely and compose a timely contribution to the system engineering process [1, 24]. Here, survivability is discussed based on a ship's susceptibility, vulnerability, and recoverability.

- **Susceptibility** is the inherent inability of the ship (including tactical measures) to avoid a hit, and it governs the probability of a hit (P_H).
- **Vulnerability** is the inherent inability of the ship to resist damage, and it governs the probability of kill (or damage) given a hit ($P_{K|H}$).
- **Recoverability** is the ability of the ship and its crew to sustain operational capability, and it governs the probability of repairing the damage (P_R). [4, 15, 21-24]

The instant killability of a ship is the product of the probability of a hit (P_H) and the probability of damage given a hit ($P_{K|H}$). Survivability (P_S) is the opposite of killability, and if only primary and secondary effects are studied without recoverability, it is given by the following:

$P_S = 1-(P_H \cdot P_{K|H})$. **Equation 1**

If the recoverability (P_R) is also included, survivability is given by the following:

$P_S = 1-(P_H \cdot P_{K|H} \cdot (1-P_R))$. **Equation 2**

Thus, the concept of survivability is probabilistic [21-23].

A ship kill does not need to result in total ship loss and can, therefore, be defined based on different severity levels, such as a system kill, where one or more components are damaged and the result is system failure; mission kill, where the ability to solve a particular mission is killed; mobility kill, where the ship losses its ability to maneuver; or total kill, where the ship is lost or must be abandoned [15, 21]. Analyses of different ship survivability levels (or kill levels) must be based on the critical components and systems identified [23].

The survivability analysis must be performed early in the design process to create conditions for survival [1]. Important technical measures for survivability include redundancy and separation (see Kim and Lee [23] for a probabilistic description of these concepts), but the discussion can also include top-level aspects, such as fleet size and composition [1, 22].

Fire on Naval vessels

Fire onboard a ship is often the consequence of an attack. Naval attacks described in open literature include the attacks on the HMS Sheffield in 1982, on the USS Stark in 1987 and on the USS Cole in 2000. In these three cases, 74 crew members were lost, many were injured, and the HMS Sheffield was lost. The HMS Sheffield and USS Stark were hit by one and two Exocet anti-ship missiles (ASMs), respectively, and the USS Cole was attacked by a suicide bomber in a small boat. For all three ships, the attack resulted in extensive physical damage and complicated fires [20, 25, 26]. The USS Stark after the attack is shown in Figure 2.

Figure 2. The frigate USS STARK (FFG-31) approximately one day after being struck by two Iraqi-launched Exocet missiles, 17th May 1987. Photo: US Navy.

The percentage of fire as a cause for naval ship loss has dramatically increased since the Second World War, and fires are now estimated to be the cause of more than 80 percent of the losses. The increase is assumed to be a result of increased levels of combustibles in the compartments, such as cables, coatings and comfort for the crew [27].

Based on the three naval fires mentioned above, it can be concluded that the fires were ignited by weapon hits, and the chain of events after the ignition depended on the hit position, weapon characteristics, ship design and efforts by the crew. Therefore, to fully analyze fire recoverability, a holistic performance assessment is necessary with respect to the fire occurrence and consequences. Generally, risk in ship design is expressed as the probability times the fatalities and is given by the following:

$$f_N(N) = \sum_{i=1}^{n_{hz}} f_{hz}(hz_i) \cdot p(N|hz_i) \qquad \textbf{Equation 3}$$

where hz_i is a fire; n_{hz} is the number of fires considered; f_N is the frequency of N fatalities per ship year; f_{hz} is frequency of fires hz_i per ship year; and $p(N|hz_i)$ is the probability of N fatalities given hz_i [11]. An extension of this model also includes other types of consequences (ship kill levels) and is presented as Equation 5.

Here, the analysis is divided into two phases to estimate the probabilities and consequences.

- *Identify fires (h_{zi}) and estimate the expected ignition frequency (f_{hz})* by analyzing how different aspects combine to affect the probability of a fire on a naval vessel. This phase represents an analysis of the ships' general susceptibility and vulnerability.
- *Identify different consequences and estimate their respective probabilities* ($p(N|hz_i)$) by describing the fire escalation and how different aspects combine to affect the severity of the fire consequences. The consequences can be analyzed in terms of aspects, such as casualties

and ship kill levels. This phase represents an analysis of the ship's fire vulnerability and recoverability.

The two phases are defined using the concept of risk (probability × consequence), Equation 3, and the above theoretical description of survivability. The phases are further developed in the following sections, where current research is examined to motivate the rationale. The proposed analysis models are presented in Figures 3 and 6.

The risk assessed by the IMO is often presented in cumulative terms with the Frequency – Number of fatalities (F-N) curve given by the following [11]:

$$F_N = \sum_{j=N}^{N_{max}} f(N_j). \qquad \textbf{Equation 4}$$

FIRE PROBABILITY

Probability of an accidental fire

Fires on civilian ships are analyzed as the result of accidents or malfunction of installed equipment, and the frequency of fire ignition per ship year must be considered for each compartment [11]. Therefore, the ignition probability is a function of the features for the respective compartment [14].

The risk-based regulatory description for fire scenarios on civilian ships is based on the safety equivalence approach in IMO SOLAS regulation II-2/17 [14]; this approach assumes that the construction material and other ship design choices do not affect the probability of fire and types of fire. The same is true for the proposed approach to risk-based ship design, where the fire probability is assumed to only be a function of the compartment characteristics, such as size and use [28].

Probability of ignition by hit

On naval ships, external threats must also be analyzed as fire causes; these fire scenarios have completely different causalities. For example, the hits on the USS Stark described in Bennet, Hagan [29] destroyed some of the structure and simultaneously ignited a fire in three adjoining compartments. Therefore, the ignition depends on the ship design and threat. Further, understanding safety (hazard-based) risks may be, to a greater extent, based on objective incident statistics, while security (threat-based) risks are considered more challenging [30] and

- often must be described and presented using expert opinions [31],
- depend on ship vulnerability and ship actions [2, 32], and
- generally include greater uncertainty [17].

Therefore, analyzing the probability of ignition by a weapon hit is much more challenging than analyzing accidental fires. Care must be used in basing the probability estimates on operational scenarios. Studies (see, for example, Aven and Krohn [17], Amer, Daim [33]; and Meissner and Wulf [34]; for maritime applications, see, for example, Bichou [30] and IMO [35]; and for military applications, see, for example, Brown and Mierzwicki [36] and Liwång, Ericson [16]) show that defining and selecting the scenario is central to the risk analysis process and should reflect the ship's operation. Generally, a scenario should be developed that considers possible futures, including the expected as well as challenging and farsighted scenarios. The probability of the future conditions should be estimated, and currently, there is an increasing focus on including uncertainties in the analysis. In addition to defining the ship tasks, the threat description is the most important input for the scenario definitions studied herein and must support a scenario definition that includes the life cycle risk. Therefore, the description must be future looking and developed specifically for the ship and its specific tactical tasks. The intelligence community is responsible for developing the threat description. Quality aspects to consider when selecting scenarios include multiple scenarios to account for uncertainty, and each scenario must be plausible, internally consistent, relevant, and contribute to the analysis.

The scenarios must consider the expected operational gain. The operational gain estimate can be based on frameworks for quantitatively measuring operational outcome, measuring effectiveness and component system performance [37]. However, the purpose of a risk-based survivability design process is to compare risk between the concepts analyzed (i.e., the relative risk), and it is unnecessary to describe the risk in absolute terms. Therefore, certain simplifications may be introduced, such as a set of scenarios that maintain an expected gain (e.g., the risk estimated for a ship to perform a certain task).

Studies (see, for example, Liwång, Ringsberg [32]) show that the analysis documented in the NATO Force Protection Directive [2] can be used in a stringent threat analysis. The threat analysis focuses not only on the threat itself but also the threat relative to the vulnerability of the ship considered. Therefore, to analyze the threat and define the scenario, the focus must be on the threat's modus operandi, as well as identifying how these modus operandi can damage the ship. Further, the likelihood of different attack modus operandi is affected by the ship's tasks and susceptibility. A change in the ship design concept can change the probability of encountering a threat and/or the potential for the threat's success [2].

Cause and effect model for analyzing the probability of a fire on a naval vessel

Based on the above description, the probability of accidental fires is limited to the effects of the compartment characteristics, typically, the size and use. On the other hand, the probability of a hit results from a long chain of causes and effects, beginning with the ship tactics and tasks as illustrated in Figure 3. Multiple scenarios are necessary to consider the uncertainty, and each scenario must be plausible, internally consistent, relevant, and contribute to the analysis. Therefore, the model in Figure 3 describes the operational scenario and is used herein to describe how different aspects combine to affect the probability of a fire on a naval vessel. Note the strong connection between the ship design concept and the probability of fire. The design concept directly affects tactics, ship susceptibility and ship vulnerability and indirectly affects the threat characteristics, which depend on the ship characteristics. The accidental fire and its causes (e and v) described in Figure 3 is typical for modeling/analyzing the ignition process on civilian ships.

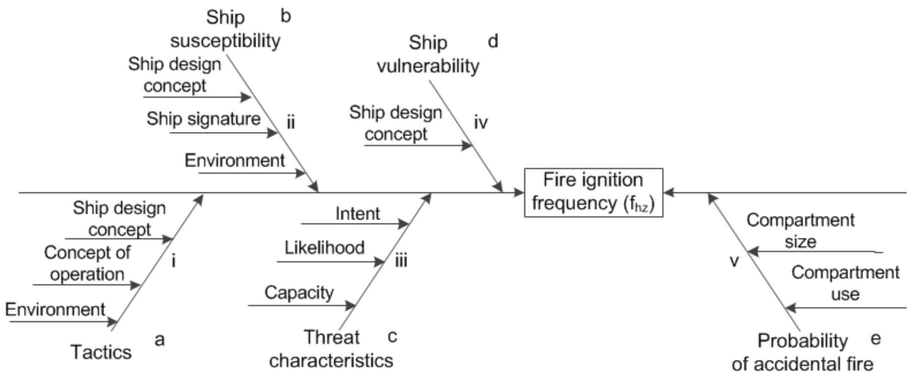

Figure 3. The proposed cause and effect model describes contributing factors to fire ignition; the proposed model is based the approaches and research described in Table 1. The model is used here to describe features for exploration and analyses.

Table 1. Summary of approaches and research used to develop the model proposed in Figure 3. The index references the indices (a-e and i-v) in Figure 3.

Relation	Index	Research area	Example of references
Tactics	a, i	Operational research, scenario definition	Hughes [38], Liwång, Ericson [16]
Susceptibility	b, ii	Naval ship design	Vaitekunas and Kim [39]
Threat characteristics	c, iii	Threat analysis	NATO [2], Liwång, Ringsberg [32]
Vulnerability	d, iv	Vulnerability	Lou [40], Schofield [41]
Accidental fire, ignition and causes	e, v	Civilian fire risk analysis	Pawling, Grandison [11], Vassalos [14]

Causes, effects and interdependencies for each area (a-e) in Figure 3 must, when calculating risk be more closely defined and examined; however, they are not further analyzed or described in this study.

In approaches for civilian ships, each fire and compartment is considered independently, and the fire analyses that include more than one compartment are only considered as escalations. For naval ships, the compartments cannot always be considered intact upon ignition nor can simultaneous ignitions in several compartments be considered independent (e.g., the real fire in the three compartments presented in Bennet, Hagan [29]). This approach leads to at least one fire for each compartment and multiple cases that represent relevant combinations of compartments. Therefore, fires cases on naval ships are more complex and greater in number.

The vulnerability is assessed based on a hit and the output of the susceptibility analysis. Currently, several tools are available for vulnerability analyses of ships. Certain tools, such as Prevent [42], are intended for early design evaluation, and others, such as Survive [41], were developed for a full 3D analysis of ships. Typically, these tools use weapon type and hit characteristics as input and use a Monte Carlo method to assess the probability of different types of damage, physical damage, component damage and ship functions damage. Most often, blast, fragment, underwater shock, flooding and system functional damages are analyzed, and more advanced tools, such as Survive, also include fire ignition, fire spread, firefighting and evacuation. The tools are experimentally validated through trials and data from actual attacks (see, for example, Hartmann and Magnusson [43] and Schofield [41]).

In sum, the reliability and consistency of identifying fires depend on well-specified tasks, types of operation and type of threat. Without these specifications, assumptions are required, which can reduce the reliability. The reliability also depends on a structured and documented analysis of how the different aspects (in Figure 3) interact. The validity and relevance depend on the specified tasks and threats, which respond to the actual ship use, and the scenarios and analyses, which must sufficiently consider the complexity of the ship operations.

Example: small naval vessel under littoral conditions

Table 2 exemplifies certain points described. The table divides the types of ignition into three general types: the first, *local ignition intact compartment*, represents accidental fires in accordance with the civilian approach described above; the second type, *local ignition added complexity*, represents weapon hits that do not detonate and only yield limited physical damage; and the third type, *multiple ignition added complexity*, represents detonating weapons or several hits, including, for example, added fuel. The data for accidental ignition are estimated based on fire statistics [44]. The table divides the operations into three types (where none represents a naval war). The threat probability for certain types of operations must be set by the naval administration. Based on open sources [27, 45, 46], it is assumed herein that the ship is fired upon once in 30 years during standard operations and once every year during high-risk military operations. To avoid concerns with classified information, it is assumed herein that, given a shot against a standard military ship, the probability of a hit and local ignition is 10 percent and of a hit and multiple ignitions is 10 percent. For a ship design concept that was produced with an effort to lower susceptibility (signature management, passive and active protection, etc.), the respective hit probabilities are assumed to be ten times lower.

Table 2. Probability magnitude for different types of ignition. The number of cases for each type of ignition (n_{hzLI}, n_{hzLA}, and n_{hzMA}) is assumed herein to be 10^2. To calculate the magnitude of the ignition probability for each type of ignition, the probability of ignition is assumed to be almost evenly distributed (between the given minimum and maximum values) over the different compartments. The variables are annotated in accordance with Equation 3.

		Expected ignition frequencies, f_{hz} (per ship year)				
		Civ op	Std mil op		High risk mil op	
Case type	**Case, hz**		**Std ship**	**Low susc.**	**Std ship**	**Low susc.**
Local ignition intact compartment (LI)	hz_{LI_1}	min 10^{-5}	min 10^{-5}	min 10^{-5}	min 10^{-5}	min 10^{-5}
-	hz_{LI_2}	-	-	-	-	-
-	:	-	-	-	-	-
-	hz_{LI_n}	max 10^{-3}	max 10^{-3}	max 10^{-3}	max 10^{-3}	max 10^{-3}
Total, case type		**10^{-2}**	**10^{-2}**	**10^{-2}**	**10^{-2}**	**10^{-2}**
Local ignition added complexity (LA)	hz_{LA_1}	0	min 10^{-6}	min 10^{-7}	min 10^{-4}	min 10^{-5}
-	hz_{LA_2}	-	-	-	-	-
-	:	-	-	-	-	-
-	hz_{LA_n}	0	max 10^{-4}	max 10^{-5}	max 10^{-2}	max 10^{-3}
Total, case type		**0**	**10^{-3}**	**10^{-4}**	**10^{-1}**	**10^{-2}**
Multiple ignitions added complexity (MA)	hz_{MA_1}	0	min 10^{-6}	min 10^{-7}	min 10^{-4}	min 10^{-5}
-	hz_{MA_2}	-	-	-	-	-
-	:	-	-	-	-	-
-	hz_{MA_n}	0	max 10^{-4}	max 10^{-5}	max 10^{-2}	max 10^{-3}
Total, case type		**0**	**10^{-3}**	**10^{-4}**	**10^{-1}**	**10^{-2}**
Total, prob. of ign. per ship year		**10^{-2}**	**10^{-2}**	**10^{-2}**	**10^{-1}**	**10^{-2}**

To obtain ignition probabilities, the characteristics of different hit types must be estimated. Therefore, to define the cases of fire (hz_i), the intended operation types and threats must be analyzed with respect to, for example, the weapon type and hit probability for the different compartments. The traditional ship threat is an ASM that is most often equipped with a radar or infrared seeker. Most nations have modeled how such missiles are assumed to operate. The models are used to guide protection system designs but can also be used to generate assumptions for the probabilistic threat description. An example of an assumed hit position distribution for an ASM is presented by Boulougouris and Papanikolaou [15]. However, a littoral or asymmetric scenario also introduces exposure to unguided weapons developed for land conditions, such as hand-held anti-tank grenade launchers (RPGs) [45]. Therefore, the probability distribution of the hit position for short distances will depend on the shooter's perceptual predisposition, beliefs and assumptions rather than technical aspects. Figure 4 shows the results of a survey on aim-point selection under a littoral scenario; the results show that, even though there are different approaches available, the aim-point was concentrated at the bridge. The differences between hit distributions for different threats are highlighted in Figure 5.

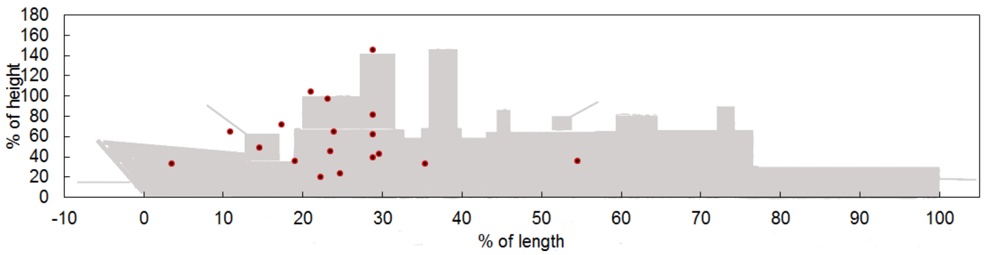

Figure 4. Aim-point distribution. Shooter priority instructions: (1) hit and (2) maximum effect; sinking was not a priority.

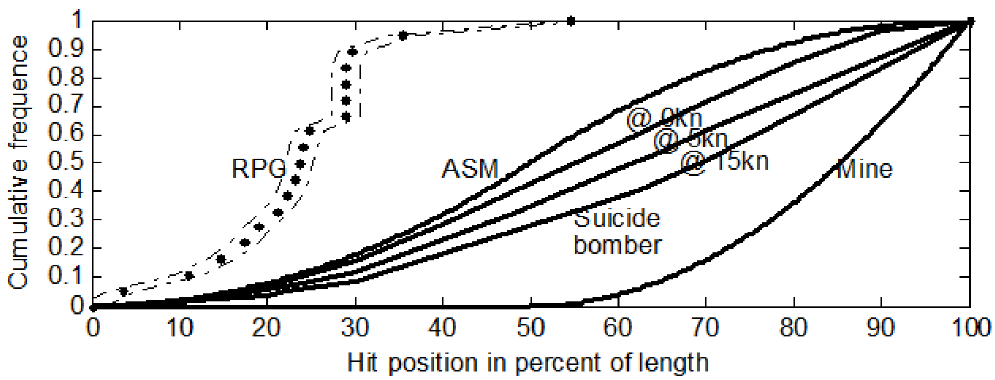

Figure 5. Cumulative distribution for the probability of a hit position for RPG, ASM, suicide bomber at various ship speeds and mine. The RPG distribution was developed based on the data presented in Figure 4. The ASM and mine distributions were developed based on Boulougouris and Papanikolaou [15]. For the suicide bomber, the distribution varies with the ship speed, and the distribution was developed based on the actual attacks presented in King [46].

Figure 5 shows that 80 percent of the RPG hits are concentrated between 12 and 33 percent of the ship length; the same figures for the ASM hits are 23 and 77. For a suicide bomber, the hit position probability and susceptibility vary with ship speed. The hit position probability differs between weapons and, for the RPG attacks, the appearance of the ship, especially the position of the bridge, is linked to the hit probability distribution. Therefore, the ignition probability for different areas and types of ignition will wary depending on the type of operation, threat and type of weapon in accordance with Figure 5, and an analysis using the model in Figure 3 will lead to the case probabilities exemplified in Table 2. For example, the ignition frequency (f_{hz}) for weapon-ignited fires depends on the location of the compartment in the ship, which is not the case for accidental fires.

FIRE CONSEQUENCES

Civilian development

The framework proposed in risk-based ship design sums the fire risk, the probability times the expected number of fatalities for each compartment, and the escalation outcome in accordance with Equation 3. The models and tools used to evaluate fires and evacuation developed for the civilian maritime industry are generally probabilistic [28, 47, 48]. Themelis and Spyrou [48] extensively describe one such approach; the description includes fire growth intensity, restriction of the heat release rate, flashover occurrence, the final decay, fire suppression triggered and the effect of manual intervention.

The analysis also includes aspects such as evacuation effectiveness and the impact of firefighting. Estimates on the impact of firefighting are based on experiences on cruise vessels [14] or in buildings [48].

Therefore, to estimate the fire process and the subsequent consequences, the general fire process must include effects from compartment fire characteristics, different forms of fire protection and manual intervention.

Analyzing the consequences of fire on board naval vessels

The general process for a fire on naval vessels is assumed herein to be the same as described above for civilian ships, and the recoverability depends on a physical description of the damage, its effect on ship functions and how the fire can be temporarily or permanently attended to by the crew.

For a naval ship intended to survive an attack, an analysis of the consequences cannot be limited to fatalities; further, the operational capabilities of the ship after the fire must be considered. This analysis should be performed considering ship kill levels and focusing on survivability of the critical components identified.

The consequences of each fire must be assessed given a type of fire ignition, examining the fire conditions for a compartment or combination of compartments, and considering the effectiveness of passive and active suppression [11, 19]. The probability of each case must be estimated based on the vulnerability analysis based on the survivability scenarios and compartment characteristics. Most fires have a minor risk contribution, minor local fires, for which the consequences can be less rigorously estimated. For the few types of fires with potentially serious consequences, escalation and the effects of fire suppression must be more closely examined.

In a more extensive examination, firefighting must be included. The conditions for firefighting on board naval vessels are generally better than on board civilian ships [19], which was exemplified by the effective firefighting onboard the USS Cole and USS Stark after they were attacked [20, 26]. The two central aspects for effective firefighting are the time to intervention and the crew's capacity [48].

The crew's performance is influenced, but not necessarily determined, by a broad range of human, technical, organizational and environmental factors [49]. Therefore, analyzing the crew's contribution to recoverability includes specific challenges. There are gaps in the literature on the effects of security threats as stressors on the crew's performance. Typically, stress leads to poor decision making. Therefore, under conditions with a perceived security threat there are fewer resources to perform the task and the likelihood of errors increases. However, the literature includes research on the likelihood of human errors in maritime crisis situations, such as offshore evacuations [50], and on causation factors, such as the probability that a crew member does not act as he or she should [51]. Such frameworks can also be used to assess other types of crises. In such an analysis, it is important to acknowledge that well-learned skills and well-rehearsed tasks require less attentive control and, thus, performance of these tasks is less affected by stress [52].

Cause and effect model for analyzing the consequences of a fire on a naval vessel

The naval vessel fire analysis includes additional cases as shown in Table 2. These additional cases include an interaction between the hit and compartment definition.

For a naval ship, it is also relevant to analyze the ship's operational capability after the hit (survivability level). Therefore, the analysis cannot be limited to analyzing consequences based on casualties, but it must also examine the different kill levels. Further developing Equation 3 yields the following expression:

$$f_{Ki}(Ki) = \sum_{i=1}^{n_{hz}} f_{hz}(hz_i) \cdot p(Ki|hz_i) \qquad \textbf{Equation 5}$$

where f_{Ki} is the frequency for the kill level Ki per ship year; and $p(Ki|hz_i)$ is the probability that the kill level Ki will occur for a given hz_i.

Under both civilian and military conditions, the fire case analysis includes the duel between the fire escalation and fire protection, for which different aspects of the fire must be analyzed. Figure 6 shows the cause and effect diagram for fire cases proposed herein, which is based on the above description and describes the process for how different aspects combine to affect the severity of the fire consequences in each compartment or combination of compartments. The consequences can be analyzed in terms of aspects such as casualties and ship kill levels. The process (j-n) and the lower half of the diagram (ix-xi) describe the effects and causes that are typically analyzed for civilian ship fires.

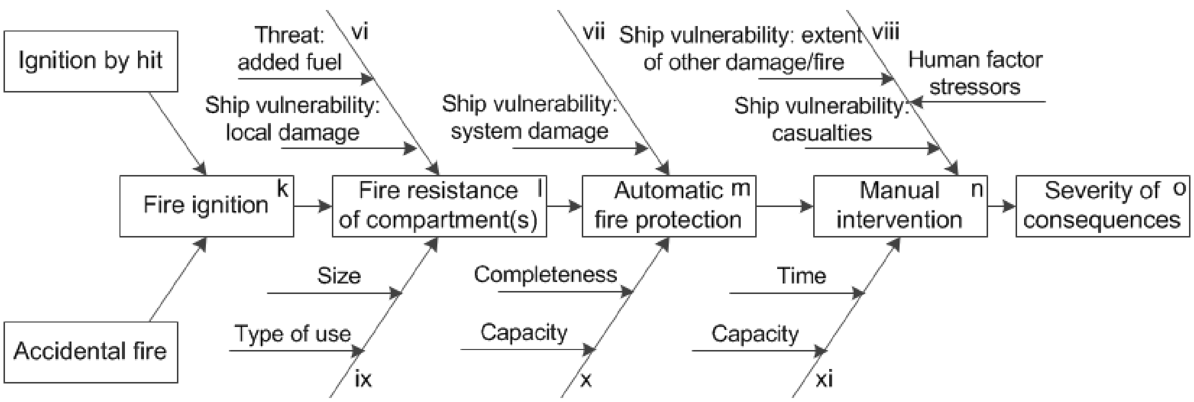

Figure 6. Proposed process cause and effect diagram for fire analyses; the proposed model is based on approaches and research in accordance with Table 3. The model used herein describes how different aspects combine to affect the severity of the fire consequences.

Table 3. A summary of the approaches and research used to develop the model proposed in Figure 6. The index references the indices (k-o and vi-xi) in Figure 6.

Relation	Index	Research area	Example of references
General fire escalation	k, l, m, n, o	Civilian fire risk analysis	Vassalos [14], Themelis and Spyrou [48]
Civilian fire escalation causes	ix, x, xi	Civilian fire risk analysis	Vassalos [14], Themelis and Spyrou [48]
Compartment(s) fire escalation causes	vi	Military fire analysis	McGeorge and Høyning [19], Schofield [41]
Automatic fire protection effectiveness	vii	Military fire analysis	Kim and Lee [23], Schofield [41]
Manual firefighting effectiveness	viii	Human factors and fire analysis	Crum, McMichael [20], Musharraf, Hassan [49]

Causes, effects and interdependencies for each area (k-o) in Figure 6 must, when calculating risk be more closely defined and examined; however, they are not further analyzed or described in this study.

The reliability of the fire consequences analysis requires that the relevant damages can be modeled and that the aspects included, such as the fire characteristics of the construction material, fire insulation, fittings, and firefighting priorities as well as procedures, are well-defined. The validity of the analysis depends on that the data and models used describe the military conditions.

Example: small naval vessel under littoral conditions, continued

Based on the example in Table 2, an analysis of the fire consequences is illustrated in Table 4 with event tree diagrams that follow the structure of Figure 6. The table provides typical values; for a real analysis, each compartment configuration must be separately analyzed. The fault tree represents the fire escalation and conditions as well as efforts to stop the escalation. The local ignition values were estimated from maritime statistics [44]; the multiple ignition values are based on maritime statistics from Crum, McMichael [20], Langworthy, Sabra [26] and the US Navy [25].

Table 4. Magnitude of the risk contributed (where the only consequence is lost life). All probabilities are based on an assumed ignition. The variables were annotated in accordance with equation 3.

	Probability for				
Ignition type	local fire escalation	failure of automatic syst.	failure of manual firef.	Lost lives due to fire, N	$P(N\|hz_i)$
Local ignition intact compartment	yes 10^{-1}	yes 10^{-1}	yes 10^{-1}	10^{1}	10^{-3}
			no	10^{0}	10^{-2}
		no		0	10^{-1}
	no			0	$<10^{0}$
Local ignition added complexity	yes 10^{-1}	yes 10^{-1}	yes 10^{-1}	10^{1}	10^{-3}
			no	10^{0}	10^{-2}
		no		0	10^{-1}
	no			0	$<10^{0}$
Multiple ignitions added complexity	yes 10^{0}	yes 10^{0}	yes 10^{-1}	10^{2}	10^{-1}
			no	10^{1}	$<10^{0}$
		no		10^{0}	10^{-1}
	no			0	10^{-1}

As shown in Table 4, the consequences are based on the ignition case description. Information on the types of operation and threat characteristics is unnecessary for the consequence analysis.

Table 4 clearly shows that the effects of the hit, such as added fuel, damage to the ship's systems or casualties, must be the input for the analysis to correctly estimate the fire escalation. The fire insulation, for example the effects of Fiber Reinforce Plastics (FRP), must also be considered.

In the fire analysis, experiments are important [18]; fire experiments have been performed for naval vessels, such as the experiment described in Bennet, Hagan [29] and McGeorge and Høyning [19]. However, results from many such experiments are not documented in the publically accessible academic literature. Further, the different kill levels must be analyzed based on Equation 5, using the concept of fire escalation in accordance with Table 4.

An analysis on the failure of manual firefighting must include the crew performance and, as shown in Table 4, firefighting is most important for complex ignition cases. As described above, multiple approaches can be used to estimate crew performance and model the crew effectiveness in a recoverability scenario. The literature also includes research on how incident statistics can be analyzed to support selection of risk control measures, including crew performance [53]. Herein, expert opinions are central, but it is important that the experts have relevant experience and, if possible, use empirical data and calibrate techniques [50]. To validate model output, historical events must be analyzed, full-scale experiments must be performed, and the effects of current training must be analyzed. One example of a relevant, full-scale experiment is the Operational Sea Training performed by the Flag Officer Sea Training for the UK Royal Navy [54]. Structurally used the experience and data from such experiments could be used to develop naval specific human error and causation factor models.

CONDITIONS FOR A RISK-BASED APPROACH TO NAVAL SHIP RECOVERABILITY

Example: small naval vessel under littoral conditions, continued

For standard military operations, Table 2 shows that weapon hits yield a lower ignition frequency compared with accidental fires. However, as shown in Table 5, the risk contribution from weapon hits is several orders of magnitude greater than from accidental fires. Therefore, given the values used herein, considering aspects such as general susceptibility can be an effective way of reducing the fire risk, and ignoring the effects of different design choices will risk penalizing design choices that can positively effect on the combat effectiveness.

Table 5. Magnitude of the fire risk contribution from different types of ignition and operation developed based on Tables 2 and 4.

Case type	Risk contribution				
	Civ op	Std mil op		High risk mil op	
		Std ship	Low susc ship	Std ship	Low susc ship
Local ignition intact compartment	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
Local ignition added complexity	0	10^{-4}	10^{-5}	10^{-2}	10^{-4}
Multiple ignitions added complexity	0	10^{-1}	10^{-2}	10^{0}	10^{-1}
Total, fire risk per ship year	$\mathbf{10^{-4}}$	$\mathbf{10^{-1}}$	$\mathbf{10^{-2}}$	$\mathbf{10^{0}}$	$\mathbf{10^{-1}}$

As expected, the risk contribution from fire onboard naval ships is considerable compared with civilian operations, especially for high risk operations (Figure 7). Thus, there are also societal reasons for considering fire risk on naval vessels, and Figure 7 shows that the level of risk is greater for incidents with potentially great consequences compared with high-frequency incidents. When standard military operations using low-susceptibility ships are compared with high-risk operations using a standard ship, the greatest uncertainties (possible variation in risk) are associated with the operator's choices in terms of ship susceptibility and types of operation. Therefore, even if a ship fulfills its fire requirements, the fire risk can be unnecessary high if the relationship between operation, design and risk is not fully understood.

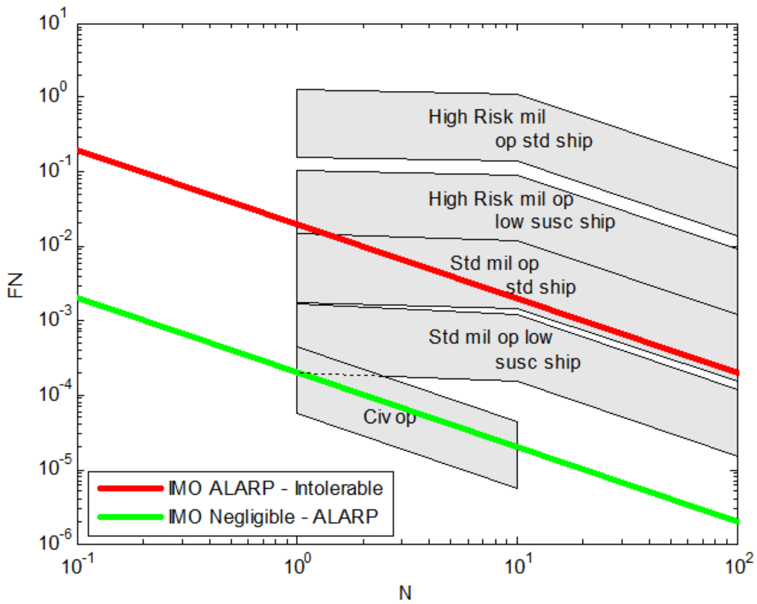

Figure 7. F-N diagram for the magnitude of a fire risk given different types of operations. The data calculated according to Equation 4 using the data in Tables 2, 4 and 5. The definition of the IMO civilian as low as reasonable practicable (ALARP) region developed from IMO [55] is included as an reference.

Analysis of conditions for a risk-based survivability approach

The purpose for introducing a risk-based approach is to identify risks in the intended operation of the ship and use this information to guide the concept development and ship design using a risk-based ship design approach, as illustrated in Figure 1. The uncertainty in the design decision making is generally high when novel concepts are developed [36]. Therefore, a rational ship design support process is necessary to avoid erroneous assumptions that affect design choices. Risk analysis is a knowledge model that may reduce this uncertainty. Based on this need, the proposed analysis models (Figures 3 and 6) in this section are used to identify critical aspects and gaps in the analysis process, specifically for naval ships.

Based on Equation 2, Figures 3 and 6, risk controls must clearly be analyzed with respect to susceptibility, vulnerability and recoverability; the total effect of these aspects must be understood to evaluate survivability. The fire risk cannot be analyzed without a general analysis of a ship's susceptibility and vulnerability with respect to relevant threats, which indicates that the analysis depends on relevant multiple operational scenarios.

Physical descriptions of fire depend on the ship specifications, and for the same operational scenario, the ship design concept will vary due to differences in the ship tactics, susceptibility and vulnerability. The example herein demonstrates that the ignition frequency (f_{hz}) for weapon-ignited fires depends on the location of the compartment; this is not the case for accidental fires. Different design concepts will also require different passive and active fire protection depending on the differences in the design and how it is manned. For example, if an FRP concept is considered, the combustible nature of FRPs can contribute to the fire in extreme fires; in other cases with higher expected frequencies, the thermal insulation of FRP will yield a smaller fire zone and contribute to survivability [19]. The smaller fire will increase the probability of successful firefighting. These aspects cannot be discerned without considering the steps described in Figure 3 and 6.

As described earlier, the critical systems must be identified to analyze the ship kill levels. These critical components and systems depend on the ship design and assumed tasks after a hit (often described as the ship survivability levels). Typical critical systems include the propulsion system and power supply.

The importance of firefighting on naval ships is highlighted in Table 4 and Figure 7, which show that firefighting is the most important aspect for reducing the probability of catastrophic consequences from complicated ignition cases because the built-in protection is insufficient for stopping the fire escalation. The reaction times and effectiveness with respect to firefighting onboard naval vessels are difficult to compare with other firefighting conditions thanks to extensive training, a high level of readiness, many crew members relative to the ship size and good firefighting equipment availability.

Certain problems have been raised for risk-based approaches, especially for defining the scenario, such as limited research and perceptions as described by Frosdick [56]. However, these problems are consistent among most analysis approaches, but heavy use of complicated tools may hide these aspects and make validation more complicated. Further, uncertainties are particularly challenging, especially for analyzing antagonistic threats [17]. On the other hand, a probabilistic approach offers a framework that is consistent from theory to the first principle tools, which has been found to improve the decision-making process when selecting among candidate survivability design principles [24].

Results

The above analysis demonstrates that considering aspects, such as general susceptibility, can be effective at reducing the fire risk, and ignoring these effects risks penalizing design options that may have positive effects on the combat effectiveness of the ship. Therefore, even if a ship fulfills fire requirements, the fire risk can be unnecessary high if the relationship between the operation, design and risk is not understood, which also indicates that considerations for one ship concept are not necessarily valid for another concept, even for the same task.

A successful analysis that correctly determines the differences between design concepts must, therefore, focus on the following aspects.

- *The relationship between design choices and the probability of ignition.* There is a relationship between general design choices (and their operational implications) and the probability of fire ignition. Characterizing this relationship depends on the threat. These relationships must be described and analyzed for multiple scenarios to account for the uncertainty, and each scenario must be plausible, internally consistent, relevant, and contribute to the analysis.
- *The state of the ship upon ignition.* The analysis of the fire escalation required to estimate the consequences depends on a physical and system description of the ship upon ignition. This description depends on the specifics of the ship and will vary for the same scenario between concepts due to differences in the ship tactics, ship susceptibility and vulnerability. Different concepts will also require different passive and active fire protection depending on the differences in how the concepts are designed and manned.

- *Complicated fire ignition cases.* The fires that require particular focus (will likely substantially contribute to the total fire risk) are defined by the weapon hit or hits and the damage it leads to. These cases differ from typical civilian ignition cases due to additional complexity from the added fuel (from the weapon), potentially multiple dependent ignitions and severe damage to the structure and systems.
- *Qualitative human factor aspects of the design.* The effectiveness of firefighting is important. Firefighting is crucial for conditions with a high risk contribution, and the effectiveness of firefighting may be high. Therefore, the analysis also depends on discerning the qualitative human factor design aspects in addition to the technical aspects.
- *Naval specific models and data.* Specific models and data as well as further validation are necessary generally and specially for signature management effects, military unique vulnerability data (such as ignition models), crew performance and the fire characteristics of the military specific equipment onboard.

In sum, generally, the reliability and validity of identifying fires depend more on a qualitative and outward-focused analysis of the ship's future. The reliability and validity of the analysis of fire consequences depend on the specific data and descriptions used. The analysis must be based on an understanding of the operational conditions. Therefore, the civilian risk-based approach to the fire risk is not applicable to naval ships because it does not include aspects of the ship design and intended operation. Further, the vulnerability tools lack this ability. However, when the fires are defined, civilian methods and tools can be used to assess the consequences if the ship specifications are suitable for naval ships.

Therefore, naval-specific research and validation are necessary. Naval-specific aspects of fire modeling have been considered, such as susceptibility effects on the probability of a weapon hit; unique military vulnerability data (such as ignition models); and the effect of a crew's competence and training on the conditions for recoverability.

DISCUSSION

Based on the need for a decision support approach to survivability design, this study describes and investigates the conditions for a military-specific fire-risk knowledge model. The aspects discussed are limited to fire survivability and exemplified by a discussion comparing different design concepts for small warships under littoral conditions. Based on the proposed cause and effect models and the littoral example, this study suggests key aspects of a risk-based methodology. This study examines the conditions for a risk based approach, not in detail how the analysis of fires should be performed.

In sum, based on the analysis, the approaches to risk-based ship survivability must be further developed, especially to ensure that the ship operational conditions are included in the analysis. For example, erroneous assumptions on the causality of fire on naval vessels have been reported, and the effect of hull material choice on susceptibility and vulnerability is ignored in the cost benefit analysis for analyzing safety on naval ships as proposed by McGeorge and Høyning [19], which indicates a need for a more stringently developed holistic ship design process. Further development of support for risk-based decisions, approval and control is also necessary.

In risk management generally and survivability especially, both qualitative and quantitative analyses are necessary, and consideration of both perspectives in the analysis should be ensured, especially to determine weaknesses in areas such as risk perception, uncertainties and safety culture.

Risk-based decisions are not discussed here, but how risk-based knowledge models should be used in the design decision-making process must also be further investigated. Examples of questions that merit investigation include areas where it is not always rational to minimize risk:

- The approach discussed could both present risk in terms of fatalities (typically as an F-N curve) and probabilities for different kill levels. However, it is not given that a concept with the lowest probability of a specific kill level is the concept with the lowest risk in respect to the crew.
- How much can the vulnerability and recoverability measures (such as the level of fire protection) be reduced due to lower susceptibility (i.e., what is the minimum allowable level of fire protection)?
- To what extent can the analysis results be trusted, and how should uncertainties be presented to the decision maker (e.g., is the low risk a result of a superior design concept or low-validity data and a lack of robustness)?
- The identified operational scenarios and fires cannot be interpreted too narrowly. For example, that the RPGs are most often shot towards the bridge cannot be the basis for ignoring protection in other areas.

These limitations require further critical examination, and the complex analysis should be applied with caution but with a focus on further developing the approach because a structured approach, despite its limitations, supports the process of selecting among candidate survivability design principles and specific survivability measures. It also supports the transfer of knowledge to fleet management, onboard tactics and crew training [6, 24]. It is also worth noting that a commitment to resilience is one way of managing uncertainties and threats in the analysis, especially relative to intentional acts, but it requires much work and training as well as [17].

CONCLUSIONS

The purpose for introducing a risk-based approach is to identify risks in the intended operation of the ship and use this information to guide concept development and ship design based on a risk-based ship design approach. The uncertainty in the design decision-making process is generally high when developing novel concepts. Therefore, a rational process is required to support design decisions, to avoid erroneous assumptions that affect future design choices and to support the risk analysis used as a knowledge model to reduce uncertainty. Without this guide, the fire risk can be unnecessary high if the relationship between operation, design and risk are not understood, even where the ship fulfills fire requirements.

From this study, it can be concluded that, although risk-based approaches are well-established in ship safety, the civilian state of the art is insufficient to guarantee the causality of the antagonistic threat to be fully captured in the analysis. Moreover, neglecting effects on how the design choices affect the fire ignition probability will risk penalizing design choices that can affect the combat effectiveness of the ship positively. Therefore, the risk analysis must be performed with respect to susceptibility, vulnerability and recoverability, and understanding the total effect from all aspects is necessary to evaluate survivability.

A successful analysis that correctly considered the differences between design concepts must, therefore, focus on the relationship between design choices and ignition probability; the state of the ship upon ignition; complicated fire ignition cases; qualitative human factor aspects of the design; and naval specific models and data.

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