# 7. Risk-Based Fire Safety Design Framework for Modern Cruise Vessels: An Integrated Approach to Enhanced Maritime Safety

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**Abstract:** Fire safety aboard cruise ships represents one of the most significant safety challenges within the maritime sector. The operational context of these vessels—isolated at sea, accommodating thousands of passengers and crew, integrating complex systems within constrained spaces, and offering limited evacuation options—results in a unique and elevated risk profile. Addressing this complexity requires a shift from conventional prescriptive approaches to more adaptive, risk-based approaches. This paper proposes a comprehensive framework for the application of risk-based fire safety design on cruise ships. It critically examines the limitations of traditional prescriptive (rule-based) approaches, which may restrict design flexibility and fail to account for the specific operational and architectural characteristics of modern cruise vessels. By contrast, the risk-based approach allows for tailored safety solutions that align with a vessel's unique features while ensuring regulatory compliance and maintaining high levels of safety. The study analyses common fire hazards encountered on cruise ships, including ignition sources, combustible materials, and system vulnerabilities. It then introduces advanced mitigation strategies encompassing fire prevention, detection, containment, and evacuation planning. The proposed framework also facilitates the integration of innovative technologies and design concepts, enabling the development of safer and more efficient cruise ships. The findings underscore the importance of adopting risk-based (performance-based) design philosophies to address emerging risks and support continuous improvement in maritime fire safety.

**Keywords:** Risk-based fire safety design; Cruise ships; Fire prevention strategies; Fire mitigation strategies; Regulatory compliance

## 1. Introduction

Fire accidents aboard modern cruise ships (see Figure 1) represent one of the most critical safety challenges in contemporary maritime operations. Unlike land-based structures, ships present distinctive difficulties during fire emergencies: they operate in isolated marine environments, offer limited escape routes, and contain confined internal spaces that can accelerate the spread of fire. Moreover, they rely exclusively on onboard firefighting systems, with no immediate access to external emergency assistance. The consequences of such incidents can be severe, potentially compromising the structural integrity of the vessel and endangering the lives of thousands of passengers and crew members.

Historically, maritime fire safety has been governed by prescriptive regulatory frameworks, most notably through the International Maritime Organization's (IMO) Safety of Life at Sea (SOLAS) Convention. These regulations establish detailed requirements for fire detection, prevention, and suppression systems. While such standards have contributed significantly to improvements in onboard fire safety, they are often perceived as inflexible and may not adequately address the complexities introduced by contemporary vessel designs and evolving operational practices. Furthermore, prescriptive approaches do not necessarily facilitate the optimal allocation or integration of fire safety resources.

In response to these limitations, the risk-based design (RBD) approach has emerged as a more adaptive and holistic methodology for enhancing fire safety at sea. Rather than focusing solely on compliance with predetermined regulatory criteria, RBD encourages ship designers and operators to systematically identify, assess, and mitigate specific fire risks based on the vessel's unique design characteristics and operational profile. This approach promotes the development of tailored safety solutions that allow for greater flexibility and innovation, while maintaining—or exceeding—established safety standards.

This paper proposes a framework for the implementation of risk-based fire safety design in cruise ships. It examines common causes of onboard fire accidents, analyses lessons learned from historical events, outlines methodological approaches for fire risk assessment, explores design considerations particular to cruise vessels, and presents advanced strategies for risk mitigation. Ultimately, the objective is to contribute to the ongoing evolution of maritime fire safety, shifting from a prescriptive, one-size-fits-all model towards a performance-based paradigm that more effectively safeguards human life, vessel integrity, and the marine environment (Xie, 2001; IMO, 2001; Spyrou et al., 2020).


Figure 1. Icon of the Seas, The World's Largest Modern Cruise Ship (Adapted from: Agency Riviera Maya, 2025).

## 2. Primary sources of fire on board cruise ships

Fire hazards aboard cruise ships arise from a variety of sources, each characterized by distinct risk profiles that require systematic consideration within a comprehensive safety design framework. A thorough understanding of these sources is essential for the development of effective risk-based strategies for fire safety (Luo and Shin, 2019).

### 2.1. Engine room fires

According to Koromila and Spyrou (2019), the engine room is the most common point of origin for shipboard fires, as evidenced by maritime accident statistics. Such incidents typically stem from a combination of interrelated factors, including:

1. Fuel or lubricant leaks coming into contact with hot surfaces
2. Overheating of propulsion machinery components
3. Electrical malfunctions within power generation systems
4. Inadequate maintenance of mechanical equipment

Fires in the engine room are particularly hazardous due to the concentration of flammable materials and the critical role of these systems in the vessel's propulsion and electrical operations. On 7 September 2015, while docked at the Port of Charlotte Amalie in St. Thomas, U.S. Virgin Islands, the Carnival Liberty experienced a fire in its engine room (see Figure 2, below). The fire originated in the ship's aft engine room and was attributed to a leak in a fuel supply line, which sprayed fuel onto a hot surface, igniting a blaze. The crew activated the ship's fire suppression systems, and the fire was extinguished without injuries to passengers or crew. However, the incident resulted in the cancellation of the remainder of the cruise. The National Transportation Safety Board (NTSB) investigation highlighted the importance of regular maintenance and inspection of fuel lines and components to prevent such occurrences (NTSB, 2017). This incident underscores the critical nature of engine room fires and the necessity for stringent maintenance protocols and rapid emergency response measures to ensure the safety of passengers and crew.

Figure 2. The fire aboard the Carnival Liberty caused by loose bolts in the engine room (The Maritime Executive, 2017).

## 2.2. Electrical system failures

Modern cruise ships are equipped with extensive and complex electrical systems that support a wide range of functions, from navigational equipment to passenger amenities. Faulty electrical wiring, as identified by Koromila and Spyrou (2019), is a major fire risk across all vessel types. Electrical fires may arise from various causes, including:

1. Short circuits in ageing wiring systems
2. Overloaded electrical circuits
3. Substandard installation practices or inadequate repairs
4. Water ingress into electrical components
5. Failure of protective electrical devices

Given the widespread distribution of electrical infrastructure throughout a cruise vessel, such failures can initiate fires in virtually any onboard location. On 25 June 2024, Seatrade Cruise News (2024) reported that a fire broke out aboard the Icon of the Seas, the world's largest cruise ship operated by Royal Caribbean International (see Figure 1, above), while docked at Costa Maya, Mexico. The minor blaze occurred in a crew area and was attributed to an electrical fault. Although the fire caused a temporary loss of power, it was swiftly extinguished, and no injuries were reported. The ship continued its scheduled itinerary without further incident.

## 2.3. Galley and food service areas

Galleys constitute one of the most concentrated fire risk zones on cruise ships due to the continuous, high-volume cooking operations required to serve thousands of meals each day. Galley fires, as noted by Rhine (2024), are frequently caused by the following factors:

1. Unattended cooking activities, particularly during peak meal preparation periods
2. The accumulation of grease in exhaust hoods, ventilation ducts, and on cooking surfaces, which may ignite when exposed to elevated temperatures
3. Malfunctioning or poorly maintained kitchen appliances such as ovens, deep fryers, and other high-temperature cooking equipment

The combination of sustained heat sources, flammable cooking oils, and continuous use renders galley areas particularly vulnerable to onboard fire outbreaks. A notable example of a fire incident originating in a galley occurred aboard the Costa Diadema (shown in Figure 3, below) on 14 August 2024. In the early hours of the morning, a fire ignited in the main galley while the vessel was enroute to Stavanger, Norway. The ship's automated fire suppression system, along with the prompt response of the crew, successfully contained and extinguished the blaze, resulting in no injuries or significant damage. The incident did not disrupt the cruise schedule, allowing passengers to continue their journey with minimal interruption. This event underscores the critical importance of stringent safety measures and the effectiveness of crew emergency training in managing fire risks within food service areas of cruise ships.


Figure 3. Costa Diadema is a Dream-class cruise ship owned by Carnival Corporation and operated by Costa Crociere. (Source: CruiseMapper, 2024)

## 2.4. Accommodation areas

Passenger and crew accommodation areas present distinct fire risks due to:

1. Electrical appliances in cabins (hair dryers, curling irons, personal electronic devices)
2. Smoking materials improperly discarded
3. Combustible furnishings and decorative materials
4. Unauthorized use of heating devices or open flames

The high occupancy of these areas increases both the probability of human error leading to fire ignition and the potential consequences of fire events. The fire aboard the Star Princess on 23 March 2006 serves as a notable example of a fire accident originating within the accommodation spaces of a modern cruise ship. As shown in Figure 4, the vessel suffered extensive damage after a blaze erupted on a passenger balcony—most likely due to a discarded cigarette igniting combustible materials. According to the UK Marine Accident Investigation Branch (MAIB), the fire spread rapidly across adjacent balconies and cabins, fueled by flammable elements such as polycarbonate partitions, polyurethane deck tiles, and plastic furniture. The absence of fire detection and suppression systems in these external areas, combined with a lack of structural and thermal barriers between fire zones and decks, significantly contributed to the fire's escalation. The incident resulted in one fatality due to smoke inhalation, injuries to several passengers and crew, and damage to nearly 300 cabins. This case illustrates the heightened fire risk within accommodation areas of cruise ships when combustible materials and insufficient fire safety measures are present (MAIB, 2006).


Figure 4. Fire onboard the Star Princess cruise ship, showing flames extending across multiple decks. (Source: USA Today, 2016)

## 2.5. Technical and service spaces

Specialized areas aboard cruise ships, such as laundry facilities, waste management zones, and technical workshops, house equipment and materials that pose unique fire hazards. These hazards typically arise from:

1. Overheating of laundry equipment
2. Spontaneous combustion of improperly stored linens
3. Presence of flammable materials in maintenance areas
4. Heat-producing repair operations, such as welding or grinding

These areas require particular attention due to the combination of high-temperature equipment, flammable substances, and ongoing technical operations, which significantly increase the risk of fire. On 20 July 1998, shortly after departing the Port of Miami en route to Key West, Florida, the Carnival Ecstasy experienced a fire that originated in its main laundry room (see Figure 5, below). The fire spread through the ventilation system to the aft mooring deck, igniting mooring lines and causing the vessel to lose power and drift. The U.S. Coast Guard responded with six tugboats to assist in firefighting and towing operations. The fire was brought under control by onboard firefighters and extinguished by approximately 9:09 PM. Fourteen crew members and eight passengers sustained minor injuries, and one passenger required extended hospitalization due to a pre-existing condition. The incident resulted in damages exceeding $17 million (NTSB, 2001).

This incident underscores the importance of regular maintenance and safety protocols in specialized areas such as laundry facilities, where equipment and materials can pose unique fire hazards.

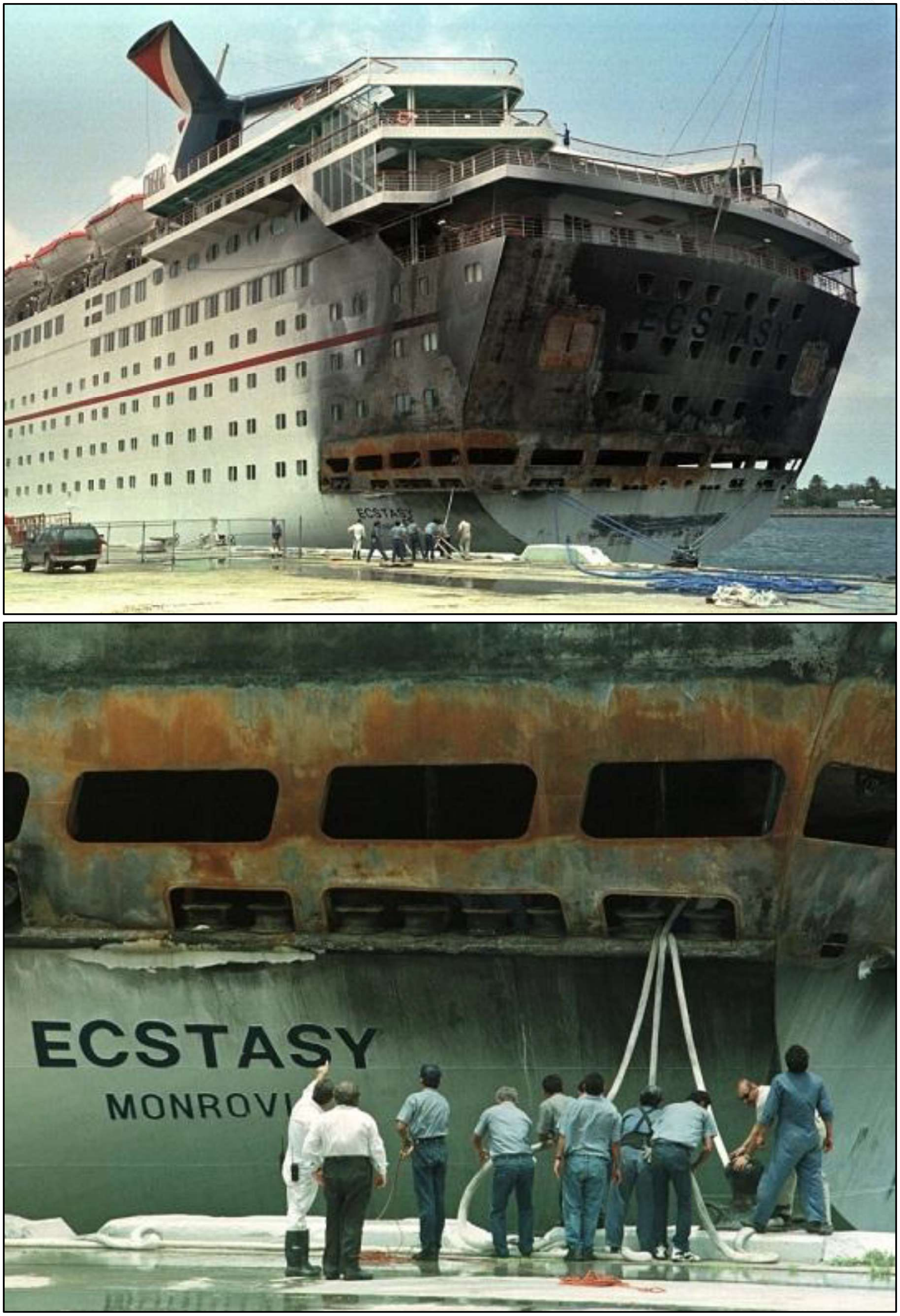


Figure 5. The aftermath of the fire aboard the Carnival Ecstasy (Walker, 2013)

### 2.6. Influence of ship layout and operations

The architectural configuration and operational dynamics of modern cruise ships play a critical role in shaping their fire risk landscape. Several design and operational factors can worsen this vulnerability:

1. The vertical arrangement of compartments across multiple decks can facilitate the upward spread of fire and smoke through stairwells, lift shafts, and service trunks.
2. Expansive open-plan areas, such as atriums, theatres, and entertainment venues, can enable rapid fire propagation and present challenges to effective compartmentation.
3. High passenger occupancy levels increase the complexity of emergency evacuation and crowd management.
4. Continuous 24-hour operations result in sustained equipment use without downtime, heightening the risk of system failures.
5. The diversity of onboard activities—including food preparation, recreational events, and technical maintenance—creates heterogeneous fire risk profiles across different zones of the vessel.

Recognizing the interplay between ship design, onboard operations, and fire hazards is essential to the development of comprehensive, risk-informed fire safety strategies tailored to the unique characteristics of cruise ships.

Cruise ships must be divided into Main Vertical Zones (MVZ) which should not be longer than 48 m, and not larger in area than 1600 $m^2$on any deck; see Figure 6. These zones are insulated from each other with an A-60 bulkhead, called MVZ bulkhead, or main fire bulkhead. These size limits are today exceeded on most of the large new cruise ships, enabled by "Alternative Design".

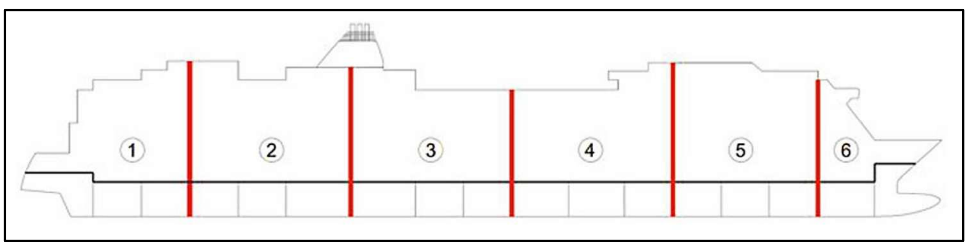


Figure 6. Main Vertical Zones (MVZ) (Aarnio, 2023)

## 3. Historical frequency analysis

Understanding the historical patterns of fire incidents on cruise ships provides critical context for risk-based design approaches. While comprehensive statistical data is limited in the provided search results, significant insights can be extracted from available information.

### 3.1. Incident frequency and trends

According to Vassalos and Fan (2016), a database comprising 577 fire incidents (including near-misses) over 111 ship-years was used to develop numerical models for fire occurrence. This equates to approximately 5.2 incidents per ship-year, underscoring the persistent nature of fire hazards in maritime operations. Although the dataset is not exclusive to cruise ships, it provides a valuable baseline for understanding fire frequency in commercial maritime contexts.

Komianos (2023) indicates that cruise ships account for the highest frequency of fire accidents among passenger vessel types, although RoPax (roll-on/roll-off passenger) vessels report higher fatality rates. This disparity may be attributed to several operational factors, including:

1. The increasing size and complexity of modern cruise vessels
2. Continuous day-and-night operations
3. Greater variety of onboard facilities and services
4. Larger numbers of passengers and crew members

Furthermore, Komianos (2023) observes that despite notable advancements in fire safety regulations and technologies, the overall frequency of fire incidents has remained relatively stable across the analysed data. This trend suggests that while large-scale fires may have become less common, core ignition risks continue to persist in maritime operations.

### 3.2. Fire origin distribution

Koromila and Spyrou (2019) indicate that, based on broader maritime statistics, engine rooms are the primary location for fire ignition on vessels, accounting for approximately 60% of all shipboard fires. Other significant areas where fires commonly originate include:

1. Galleys and food preparation areas
2. Electrical distribution panels and equipment rooms
3. Accommodation spaces
4. Technical workshops and maintenance areas

This distribution of fire origins is critical in shaping risk-based design approaches, helping to identify priority areas that require enhanced fire protection measures.

### 3.3. Fire incident severity classification

Vassalos and Fan (2016) indicate that fire incidents can be classified according to their severity and outcomes into:

1. Near-misses: Incipient fires detected and extinguished before significant damage occurs
2. Minor incidents: Fires contained within the space of origin with minimal disruption to operations
3. Significant events: Fires extending beyond the space of origin, requiring substantial firefighting effort
4. Major casualties: Extensive fire spread resulting in significant damage, potential injuries, or fatalities
5. Total loss incidents: Catastrophic fires leading to abandonment and/or complete loss of the vessel

### 3.4. Risk factors influencing incident outcomes

Historical analysis identifies several key factors that influence whether an ignition event escalates into a serious casualty (Bal Beşikçi & Tavacıoğlu, 2017; Wang et al., 2023; MoviTHERM, 2024):

1. Detection time – Early fire detection greatly improves the likelihood of successful containment and mitigation.
2. Crew response effectiveness – Outcomes depend heavily on the crew's training and the prompt, effective execution of emergency procedures.
3. Fire containment – The performance of structural fire protection measures and compartmentation plays a critical role in limiting fire spread.
4. Fire suppression system performance – The reliability and suitability of both fixed and portable firefighting systems directly impact the fire's progression.
5. Ventilation control – Effective management of airflow to the affected area is essential in reducing fire intensity and preventing escalation.

Understanding these historical patterns provides essential context for the development of risk-based design strategies. The persistent frequency of fire incidents, despite significant regulatory advancements, underscores the need for innovative, performance-based approaches to maritime fire safety—approaches that target specific risk factors rather than relying solely on prescriptive compliance.

## 4. Risk identification and assessment

Risk-based fire safety design begins with the systematic identification and evaluation of fire hazards unique to cruise vessel operations. This process integrates both qualitative and quantitative methods to construct a comprehensive understanding of potential fire scenarios, including their likelihood and potential consequences.

### 4.1. Methodological framework

The methodological framework for risk-based fire safety design on cruise ships involves a structured sequence of activities aimed at identifying, analyzing, and mitigating fire risks (Koromila & Spyrou, 2019; Pawling et al., 2012; Wang et al., 2023; Bal Beşikçi & Tavacıoğlu, 2017; Komianos, 2023). The process typically includes:

1. Hazard Identification – Systematic review of shipboard systems and operations to determine potential ignition sources and vulnerable areas, using tools such as Hazard and Operability Studies (HAZOP) or checklists derived from historical incident databases.
2. Risk Analysis – Analysis of the frequency and potential consequences of the identified hazards using qualitative tools (e.g., risk matrices) and quantitative methods such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Monte Carlo simulations, and consequence modelling tools.

3. Risk Estimation – Quantitative assessment of individual fire hazards by combining the estimated frequency of occurrence with the severity of potential consequences. This step produces numerical risk values that support the prioritization of hazards and guide the allocation of safety resources. In engineering terms, risk is typically expressed as:
$$Risk = Frequency \times Consequence$$
4. Risk Evaluation – Comparison of estimated risks against established risk acceptance criteria to determine their acceptability or the need for mitigation measures.
5. Risk Mitigation Strategies – Selection and implementation of appropriate risk control options, including technical solutions (e.g., improved suppression systems), operational procedures, and crew training enhancements.
6. Documentation and Communication – Recording assumptions, data sources, and results to support transparency and facilitate communication with stakeholders, including regulatory authorities.
7. Review and Iteration – Continuous monitoring and periodic re-evaluation to ensure ongoing effectiveness and adaptation to changes in vessel design, operations, or regulatory requirements.

### 4.2. Human factors in risk assessment

Gundić et al. (2021) emphasize that human factors significantly influence both the likelihood of fire ignition and the severity of its consequences aboard cruise ships. Key considerations include:

1. Occupancy patterns, which affect the probability of ignition and complicate evacuation dynamics.
2. Crew response capabilities, which directly influence the containment and outcome of fire incidents.
3. Passenger behavior during emergencies, which impacts evacuation efficiency and overall safety.
4. Maintenance practices, which determine the reliability and operational readiness of fire safety systems.

A comprehensive fire risk assessment must incorporate these human-related variables alongside technical and structural aspects to provide an accurate understanding of fire dynamics in the cruise ship environment.

### 4.3. Quantitative risk criteria

Risk-based design requires establishing acceptable risk criteria, which is essential for determining the effectiveness of safety measures. Risk assessment for cruise vessels usually involves evaluating two key types of risk:

1. Individual risk: The likelihood of fatality for a single person onboard.
2. Societal risk: The potential for multiple fatalities in a single event.

To compare the evaluated risks against established risk acceptance criteria, F-N curves (frequency versus number of fatalities) can be used, as referenced by Vassalos and Fan (2016). These curves provide a graphical representation of societal risk, helping to determine whether the assessed risks fall within acceptable limits. By integrating these risk assessment approaches, effective resource allocation can be made, prioritizing fire safety measures based on the most significant hazards specific to cruise ship operations.

## 5. Risk-based fire safety design principles

Risk-based fire safety design (RBFSD) marks a significant departure from conventional prescriptive approaches in maritime safety engineering. Instead of solely following predefined regulations, RBFSD adopts a performance-driven methodology that focuses on addressing specific risk factors identified through comprehensive and systematic analysis. This approach aims to optimize fire safety measures based on actual risk scenarios rather than theoretical standards. The following section delves into the core principles and practical applications of risk-based fire safety design, specifically tailored for cruise ships.

### 5.1. Conceptual framework

Risk-based fire safety design (RBFSD) fundamentally diverges from traditional prescriptive approaches in several critical ways:

1. Goal-oriented vs. specification-oriented: RBFSD emphasizes achieving broader safety objectives, focusing on actual outcomes rather than merely fulfilling specific technical requirements.
2. Holistic system perspective: RBFSD adopts a comprehensive view, addressing the interactions between various systems, spaces, and human factors, rather than considering individual components in isolation.
3. Quantitative risk evaluation: RBFSD employs probabilistic methods and consequence analyses tools to assess risk levels, providing a data-driven approach to evaluate the effectiveness of safety measures.
4. Design flexibility: By prioritizing performance over strict adherence to prescriptive rules, RBFSD encourages innovative solutions tailored to the unique characteristics of each vessel.

As Vassalos and Fan (2016) highlight, the risk-based approach allows for the integration of multiple hazards, such as fire and flooding, within a unified framework, thereby enabling a more comprehensive and effective safety assessment.

### 5.2. Regulatory framework

The implementation of risk-based fire safety design (RBFSD) is underpinned by several key regulatory frameworks and methodological tools:

1. SOLAS Chapter II-2, Regulation 17 – This regulation permits the use of "Alternative design and arrangements", allowing ship designs to deviate from traditional prescriptive requirements if they can demonstrate, through engineering analysis and justification, an equivalent or superior level of safety.
2. MSC/Circ. 1002 – This circular offers comprehensive guidelines for the approval process of alternative and equivalent fire safety measures, ensuring that proposed solutions are rigorously assessed for compliance with safety standards.
3. Fire Safety Index – Inspired by the Subdivision Index used in damage stability evaluations, the Fire Safety Index serves as a quantitative measure of both passive and active fire protection performance, facilitating the comparison of different design options within a unified framework (Vassalos & Fan, 2016).

These provisions support the practical application of risk-based design principles, fostering innovation while ensuring that safety standards are not only maintained but potentially enhanced.

### 5.3. Design elements specific to cruise ships

Risk-based fire safety design (RBFSD) enables cruise ship designers to move beyond prescriptive requirements and implement tailored safety measures that align with identified risks. The following design elements illustrate how RBFSD principles can be applied across key domains:

#### A. Space planning and compartmentation

Risk-based fire safety design allows for adaptive compartmentation strategies that reflect actual fire risk rather than rigid geometric standards:

1. Optimized Main Vertical Zone (MVZ) configuration – MVZ sizing and layout may be determined through risk analysis, focusing on minimizing fire spread and optimizing evacuation, rather than relying solely on prescriptive dimensional criteria.
2. Risk-informed structural fire protection – The application of A-class and B-class divisions can be guided by fire risk profiles of specific spaces, enabling a more efficient allocation of structural fire protection resources.
3. Strategic placement of high-risk spaces – Locating galleys, technical rooms, and other ignition-prone areas in zones that limit potential consequences enhances fire containment and protection.
4. Implementation of fire breaks in open areas – As discussed by Vassalos and Fan (2016), fire breaks between segmented superstructures are effective in restricting fire spread across large, open deck areas.

#### B. Detection and alarm systems

Detection systems can be tailored through a risk-based approach to enhance early warning capabilities:

1. Risk-based detector density – Areas identified as high-risk may be equipped with denser detector coverage, supported by fire modelling rather than uniform grid spacing.
2. Multi-criteria detection technologies – Deploying a range of detectors (e.g., smoke, heat, flame) based on expected fire signatures improves detection accuracy across different compartments.
3. Intelligent alarm management systems – Alarms can be prioritized and displayed according to the severity and location of the risk, improving situational awareness and response coordination.

**C. Suppression systems**

Suppression systems can be optimized for specific risks, improving their efficiency and cost-effectiveness:

1. Performance-based water mist systems – Tailoring suppression system specifications to individual space characteristics allows better protection compared to generic system design.
2. Targeted selection of suppression agents – Fire suppression media (e.g., $CO_2$, foam, water mist) should be chosen based on the characteristics of potential fires in each space.
3. Redundancy in critical areas – Additional or overlapping suppression systems may be justified in locations identified as having elevated risk profiles.

**D. Evacuation design**

Evacuation strategies under RBFSD leverage modelling and analysis to ensure timely and safe evacuation:

1. Evacuation modelling and simulation – Dynamic simulation of passenger and crew movement during fire scenarios supports optimal layout of escape routes and egress points.
2. Risk-informed arrangement of lifeboats and muster stations – The spatial distribution of evacuation equipment and muster areas is based on the analysis of fire scenarios and their potential impact zones.
3. Smoke management systems – Active (e.g., mechanical extraction) and passive (e.g., smoke barriers) systems are designed using Computational Fluid Dynamics (CFD) fire and smoke modelling tools to address predicted smoke movement and maintain tenable conditions.

**E. Material selection**

Fire safety performance of materials is evaluated beyond regulatory compliance through advanced testing and risk assessment:

1. Performance-based fire testing – Materials are assessed based on real fire exposure conditions, considering ignition, heat release, and flame spread characteristics.

2. Risk-weighted material distribution – More stringent fire performance requirements may be applied to areas with higher fire risk or consequences of failure.
3. Use of novel materials with protective measures – As Evegren (2010) highlights, even materials with inherent combustibility, such as Fiber Reinforced Polymers (FRP), may be safely used when paired with appropriate insulation and fireproofing strategies.

### 5.4. Implementation process

The successful application of risk-based fire safety design (RBFSD) in cruise ship development requires a structured, evidence-driven process. This approach ensures that fire safety measures are appropriately aligned with the vessel's unique risk profile. The key steps involved in implementation are:

1. Hazard Identification: A comprehensive and systematic process to identify all potential fire hazards associated with the ship's design, function, and operational profile.
2. Risk Analysis: Quantitative analysis of each identified hazard by evaluating the likelihood (frequency) of occurrence and the severity of its potential consequences.
3. Risk Evaluation: Comparison of estimated risk levels against defined acceptance criteria, such as individual and societal risk thresholds, to determine whether the design meets safety expectations.
4. Design Development: Formulation of integrated safety solutions—including detection, suppression, compartmentation, and evacuation systems—specifically targeted to mitigate the most critical risks.
5. Verification and Validation: Demonstration that the proposed design meets performance-based safety objectives through a combination of analytical modelling, physical testing, and, where applicable, independent third-party assessment.
6. Documentation: Preparation of a comprehensive safety case, including design rationale, risk analyses, verification results, and compliance justifications, to support regulatory approval and operational reference.

RBFSD offers a performance-driven alternative to conventional prescriptive approaches. By prioritizing interventions based on risk significance, RBFSD not only enhances design flexibility but also has the potential to yield superior fire safety outcomes. As Vassalos and Fan (2016) note, cruise ships designed under risk-based frameworks have exhibited improved resilience and safety performance compared to their prescriptively designed counterparts.

## 6. Risk Mitigation and prevention strategies

Effective risk mitigation and prevention strategies represent the practical implementation of risk-based design principles. These strategies must address the specific fire hazards identified through risk assessment while optimizing resource allocation based on risk significance. This section outlines advanced approaches to fire risk reduction on cruise ships.

### 6.1. Passive fire protection strategies

Passive fire protection forms the foundational layer of defence against fire spread and provides critical time for evacuation and firefighting operations.

**A. Advanced compartmentation approaches**

- Risk-based structural fire protection: Tailoring insulation requirements based on fire risk analysis rather than uniform application of A-class, B-class standards. This may include:
  1. Enhanced protection for high-risk boundaries
  2. Optimized protection for low-risk boundaries
  3. Special attention to penetrations and boundary interfaces
- Innovative fire stopping: Implementation of specialized fire barriers in critical locations:
  1. Fire breaks between superstructure sections (Vassalos & Fan, 2016)
  2. Deployable fire curtains for large openings
  3. Intumescent seals for cable and duct penetrations
- Safe application of novel materials: Composites such as FRP may be used safely with layered thermal insulation ensuring up to 60 minutes of fire resistance, as demonstrated by Evegren (2010).

**B. Material selection and lifecycle management**

- Performance-based material testing and selection: Moving beyond standard classification testing to evaluate actual fire performance in realistic scenarios.
- Risk-weighted furnishing criteria: Tighter controls apply in areas with high risk or critical functions.
- Ongoing integrity management: Passive fire protection systems are maintained through regular inspections and lifecycle assessments.

### 6.2. Active fire protection systems

Active systems detect, contain, and suppress fires, with their design optimized through risk-based approaches.

**A. Advanced compartmentation approaches**

- Multi-sensor detection networks: Integration of different detector types (smoke, heat, flame, gas) to improve reliability and reduce false alarms.
- AI-assisted detection systems: Implementation of machine learning algorithms to:
  1. Recognize fire signatures more accurately
  2. Differentiate between normal operations and hazardous conditions
  3. Predict potential fire development based on early indicators

- Risk-based detector distribution: Optimizing detector placement and density according to:
    1. Probability of fire ignition in each space
    2. Potential fire growth rates
    3. Criticality of protected areas

**B. Innovative suppression approaches**

- Targeted fixed systems: Selection of suppression agents based on specific protected hazards:
    1. High-pressure water mist for machinery spaces and accommodation areas
    2. Clean agents for electrical equipment spaces
    3. Foam systems for hydrocarbon fire risks
- Smart suppression activation: Integration of detection and suppression systems with decision support capabilities to:
    1. Confirm fire presence before discharge
    2. Target suppression to specific fire locations
    3. Adjust suppression parameters based on fire characteristics
- Redundant protection for critical areas: Implementation of multiple, diverse suppression systems in highest-risk locations.

### 6.3. Operational and human factors

Recognizing that human performance influences safety outcomes, RBD integrates operational preparedness.

**A. Crew training and response**

- Scenario-based training: Exercises reflect vessel-specific fire risks and simulate realistic emergency responses.
- Decision support tools:
    1. Real-time evacuation routing
    2. Fire progression visualization
    3. Response coordination interfaces
- Drill diversity: Fire drills encompass non-standard, high-consequence scenarios identified through risk modelling.

**B. Maintenance and inspection protocols**

- Risk-based maintenance scheduling: Prioritizing maintenance activities based on
- Continuous monitoring of critical systems: Implementation of remote sensing and condition monitoring for key fire safety systems.

- Proactive replacement programs: Scheduled renewal of components before reliability degradation rather than upon failure.

### 6.4. Regulatory framework integration

The implementation of risk-based fire safety measures must occur within existing regulatory frameworks while pursuing appropriate approvals for alternative designs.

**A. SOLAS compliance approaches**

- Equivalent safety demonstrations: Documentation of how alternative designs provide equivalent or superior safety compared to prescriptive requirements.
- Performance-based compliance: Demonstration of meeting functional requirements and safety objectives rather than specific technical provisions.
- Approval of alternatives: Following established processes for approval of innovative solutions:
    1. SOLAS Chapter II-2, Regulation 17 procedures
    2. MSC/Circ. 1002 guidelines for alternative designs

**B. Integration with safety management systems**

- Documentation of risk controls: Clear identification of risk mitigation measures in vessel safety management systems.
- Operational limitations: Establishment of any necessary operational constraints associated with alternative designs.
- Continuous improvement processes: Regular review and updating of risk assessments and mitigation strategies based on operational experience.

### 6.5. Preventive measures for specific fire hazards

Preventive strategies should be developed to address the most common fire sources aboard cruise ships:

**A. Engine room fire prevention**

- Leak detection systems: Early identification of fuel and lubricant leaks before they contact hot surfaces.
- Surface temperature monitoring: Continuous monitoring of potentially hot surfaces in proximity to combustible materials.
- Predictive maintenance: Use of vibration analysis, oil analysis, and other techniques to identify potential equipment failures before they create fire hazards.

**B. Electrical fire prevention**

- Advanced circuit protection: Implementation of arc fault detection and smart circuit protection.
- Thermal imaging monitoring: Regular inspection of electrical systems to identify potential hot spots.

- Cable management systems: Improved routing and protection of electrical cables to prevent damage and degradation.

**C. Galley fire prevention**

- Enhanced ventilation and filtration: Improved systems to prevent grease accumulation in exhaust ducts.
- Automatic cooking monitoring: Implementation of technologies to prevent unattended cooking situations (Rhine, 2024).
- Regular cleaning protocols: Scheduled cleaning of cooking surfaces, hoods, and ducts to prevent grease buildup (Rhine, 2024).

The integration of these advanced risk mitigation and prevention strategies represents a comprehensive approach to fire safety that moves beyond compliance to optimization. By directing resources toward the most significant risks, risk-based fire safety design can achieve higher levels of protection while potentially reducing unnecessary costs associated with uniform application of prescriptive requirements.

## 7. Conclusion and recommendations

Risk-based fire safety design represents a paradigm shift in the protection of cruise ships, their passengers, and crew from the persistent threat of fire. This research has explored the foundations, methodologies, and practical implementation of risk-based approaches within the context of cruise ship operations, highlighting their potential to significantly enhance safety outcomes while allowing for greater design flexibility.

Key findings from this study affirm that fire remains a persistent hazard aboard cruise vessels, with engine rooms, galleys, and electrical systems posing the highest ignition risks (Xie, 2001; Rhine, 2024; Komianos, 2023). Traditional prescriptive regulations, while valuable, apply protections uniformly across all spaces, leading to potential inefficiencies in resource allocation. In contrast, risk-based fire safety design enables the prioritization of mitigation measures according to the probability and consequence of fire events—allocating resources where they are most needed.

Recent studies have shown that integrated risk assessments are not only feasible but also provide a solid foundation for design decisions, enabling the development of comprehensive models that quantify fire scenarios ship wide (Vassalos and Fan, 2016). Ships designed under risk-based principles have demonstrated superior safety performance, particularly in societal risk metrics, compared to those built using conventional prescriptive methods.

Furthermore, the evolving regulatory framework, particularly SOLAS Chapter II-2, Regulation 17 and supporting guidelines such as MSC/Circ. 1002, facilitates the approval and implementation of performance-based alternative designs. These frameworks support innovation, enabling the use of novel technologies and materials—including fire-safe applications of FRP composites—when supported by adequate risk analysis and fire protection measures (Evegren, 2010).

Based on these insights, this study recommends the following:

- Adopt risk-based design as standard practice for fire safety on cruise ships, especially in high-risk areas such as engine rooms, galleys, and electrical zones.
- Utilize comprehensive risk models that evaluate both likelihood and consequence to guide the design and placement of fire protection systems.
- Tailor passive and active protection systems to match risk levels, including advanced compartmentation strategies, AI-enhanced detection, and smart suppression systems.
- Integrate human factors and operational strategies, including risk-informed crew training, decision-support systems, and proactive maintenance planning.
- Leverage regulatory mechanisms for alternative designs to pursue innovative yet safe solutions.
- Institutionalize continuous improvement, ensuring that fire safety strategies evolve with operational data and new technological advancements.

In conclusion, risk-based fire safety design provides a more precise, effective, and forward-looking approach to protecting cruise vessels. By focusing resources on the most significant risks and embracing innovation within a structured regulatory framework, the maritime industry can achieve higher standards of safety while promoting design efficiency and operational resilience.

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