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Barrier Failure and Fire Escalation in a Non-Class Wooden Fishing Vessel: A Structured Safety Assessment of the Hentri-I Engine-Room Fire

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ABSTRACT

Engine-room fires remain a dominant loss pathway in non-class wooden fishing vessels where combustible construction coexists with high thermal and fuel loads in confined machinery spaces. Using the Hentri-I engine-room fire (North Tanimbar, Indonesia; 3 September 2021) as an evidence-bounded case, this paper converts an official investigation into a barrier-performance model and derives engineering actions for vessel equipment, layout, and operation/maintenance. A Bow-Tie was developed around the top event "uncontrolled engine-room fire," mapping report-supported threats to prevention, detection, suppression, and consequence-management barriers. Barrier availability and effectiveness were coded from documented arrangements and survivor statements and used to prioritize feasible retrofit options for resource-constrained operators. The analysis shows a prevention set weakened by fuel/heat vulnerabilities and combustible interfaces, while escalation was accelerated by absent detection, non-isolable natural ventilation, and suppression limited to portable extinguishers without a dedicated fire pump or fixed system. These gaps compressed the effective response window and shifted the outcome toward abandonment offshore. A minimum viable retrofit package is proposed, including fuel-line hardening, heat-source shielding, ventilation isolation provisions, early detection, and a basic machinery-space suppression/attack capability, supported by a barrier-focused comparison to small-vessel safety requirements.

1. INTRODUCTION

Fire remains one of the most acute and fast-escalating hazards in fishing operations, particularly for wooden vessels that combine combustible structural materials with high thermal and fuel loads concentrated in confined machinery spaces. Engine-room fires are repeatedly identified as a dominant accident pathway in fishing fleets, with engine failures and vulnerabilities in cooling-water systems frequently implicated in incident statistics and accident narratives [1]. This recurring pattern matters because wooden hull and superstructure components can contribute to sustained burning and rapid degradation of structural integrity once ignition occurs, narrowing the time window for effective onboard suppression and safe evacuation.

The challenge is amplified in artisanal and small-scale fisheries, where safety investments compete directly with livelihoods and daily operational costs. Small-scale vessels commonly face limited fire-safety knowledge and infrequent access to structured training, while economic constraints reduce the likelihood of installing robust detection and suppression systems. Wooden construction, often without fire-retardant treatment, increases combustibility and makes fire outcomes more severe. These constraints are widely recognized as interacting causes of elevated fire risk, including deficits in maintenance capability, confined engine-room configurations, and limited onboard firefighting capacity, all of which make small-vessel fires disproportionately catastrophic compared with larger and better regulated segments of the fleet [1].

A central research problem, therefore, is not merely identifying "why fires happen," but explaining why fires on non-class, small fishing vessels so often become uncontrollable events with severe human consequences. This broad problem can be decomposed into three specific research questions: (RQ1) Which prevention barriers failed first and through what mechanisms? (RQ2) How did detection and suppression deficiencies compress the effective response time-window? (RQ3) What retrofit sequence maximizes safety impact per unit cost for resource-constrained operators? In developing-country fleets, regulatory environments and enforcement capacity can be weaker than in more tightly governed jurisdictions, and vessels may be older, retrofitted, or built outside class oversight [2, 3]. These conditions can produce persistent gaps in basic safeguards such as fire detection, active firefighting infrastructure, and emergency alerting technologies, which, when combined with combustible construction materials, shift the safety problem from prevention alone to a coupled prevention–escalation–survivability system problem.

The general solution proposed across the maritime safety literature is a multi-layered safety architecture that combines technical barriers, operational procedures, and competence development. In regulated fleets, this layered architecture is supported by inspection regimes, standardized vessel design, and mandated training, which collectively improve the availability and reliability of safety systems and reduce the likelihood that an incipient fire progresses to a loss-of-vessel event [4]. In contrast, small-scale and non-class contexts may exhibit behavioral and economic pressures that undermine equipment availability; for example, fishers may remove or deprioritize safety equipment to increase fishing capacity, illustrating how economic incentives can directly weaken the barrier set intended to protect crews [5]. Addressing the research problem therefore requires analytical approaches that can represent how technical, procedural, and organizational barriers interact under real operating constraints.

1.1 Prevention and ignition sources

Prior literature has emphasized that engine rooms are inherently vulnerable to ignition due to the coexistence of leaked fuels or oil mist, ignition sources, and unprotected hot surfaces, and that many shipboard fires initiate through the interaction of flammable releases with thermal sources [6, 7]. Recent experimental work on marine diesel leakage confirms that edge-limited hot surfaces significantly influence accidental ignition probability and combustion development in confined machinery spaces. Improvements in maintenance and fuel management are consistently highlighted as core preventive levers, since neglected checks and delayed repairs can lead to overheating or leak-driven ignition pathways. In addition to prevention, environmental control within engine rooms—including ventilation regulation consistent with widely accepted safety principles—has been described as crucial for limiting hazardous conditions and reducing fire-related incidents [8]. These studies collectively imply that fire risk in small fishing vessels is best treated as a system where design features, maintenance practice, and operational controls jointly determine ignition likelihood and escalation potential.

1.2 Detection and early warning systems

Beyond prevention, the literature provides specific technical directions for strengthening the barrier chain through detection and suppression improvements. Advanced fire detection technologies, including dual-stage systems combining rapid sensor triggering with vision-based verification, show promise in reducing false alarms while maintaining prompt response [9]. Regulated fleets increasingly rely on integrated safety technologies that support early warning and rapid response, including vessel tracking and monitoring capabilities that can accelerate external assistance [10, 11].

1.3 Suppression systems and technologies

Modern vessel design tends to incorporate compartmentalization and specialized suppression systems tailored to machinery-space fire hazards. Comparative studies demonstrate that suppression performance differs significantly between CO_2 and water mist systems, with outcomes shaped by ventilation configuration and heat release characteristics [12]. While training requirements and drills improve the probability that early-stage fires are controlled before escalation [13, 14], emerging aerosol-based suppression technologies offer potential for reduced equipment corrosion and improved agent distribution in enclosed spaces, though marine-environment reliability remains dependent on maintenance regimes [15]. In non-class contexts, however, the absence of such systems is often coupled with training deficits, making human error and delayed decision-making more consequential in emergency development [16-18].

1.4 Regulatory frameworks and small-vessel safety gaps

A closely related body of work highlights how differences between developing-country fleets and regulated fleets arise from interacting factors: weaker regulatory enforcement, older or retrofitted vessel designs, and limited access to advanced safety equipment and standardized training [2, 19, 20]. These differences create a research gap in how to operationalize "minimum viable" fire safety for small, non-class fleets without assuming full regulatory parity or costly redesign. The gap is not only technological, but also methodological: existing studies often describe risk factors, yet fewer provide a structured mechanism to translate real-world accident evidence into a prioritized set of barriers and retrofit measures that are feasible for resource-constrained operators while remaining defensible against international safety logic.

This study addresses that gap by applying a Bow-Tie and barrier-performance perspective to a documented engine-room fire on an Indonesian non-class wooden fishing vessel, using the Hentri-I accident as an evidence-bounded case. The KNKT investigation reported that the ignition source could not be confirmed due to loss of physical evidence, but it also documented a configuration that created high engine-room fire risk and noted that relying on portable extinguishers alone was insufficient for mitigation. The accident resulted in catastrophic human loss, with 26 persons missing and five survivors, underscoring the consequence severity when detection, suppression capacity, and emergency alerting are inadequate offshore. The objective is to develop a structured, engineering-actionable barrier model that identifies dominant barrier failures across prevention, detection, suppression, and emergency response, and to justify a minimum retrofit pathway aligned with internationally recognizable safety principles while remaining realistic for non-class wooden vessels operating for extended periods at sea.

2. METHOD

2.1 Study design, scope, and data source

This study employed a single-case, evidence-bounded safety engineering design to translate an official accident investigation into a structured fire-risk model for a non-class wooden fishing vessel. The primary data source was the KNKT final investigation report for the Hentri-I engine-room fire in the North Tanimbar area on 3 September 2021, which provides the event context, the documented vessel and machinery characteristics, installed safety provisions, and the accident sequence and outcomes. Because KNKT explicitly stated that the ignition source could not be determined due to loss of physical evidence, the methodological scope was deliberately defined as a barrier-performance and escalation analysis rather than an ignition-cause attribution study. This design choice aligns with Bow-Tie's strength in representing multiple plausible pathways from threats to consequences while keeping causal claims bounded to verified evidence [21, 22]. Figure 1 contextualizes the Hentri-I fire geographically by locating the incident in the North Tanimbar area, where distances from major shore facilities plausibly constrain external response options and elevate the importance of onboard detection, suppression, and communications performance. This spatial context is treated as part of the case boundary, informing how rescue latency and limited shore support can amplify the consequences of barrier degradation.

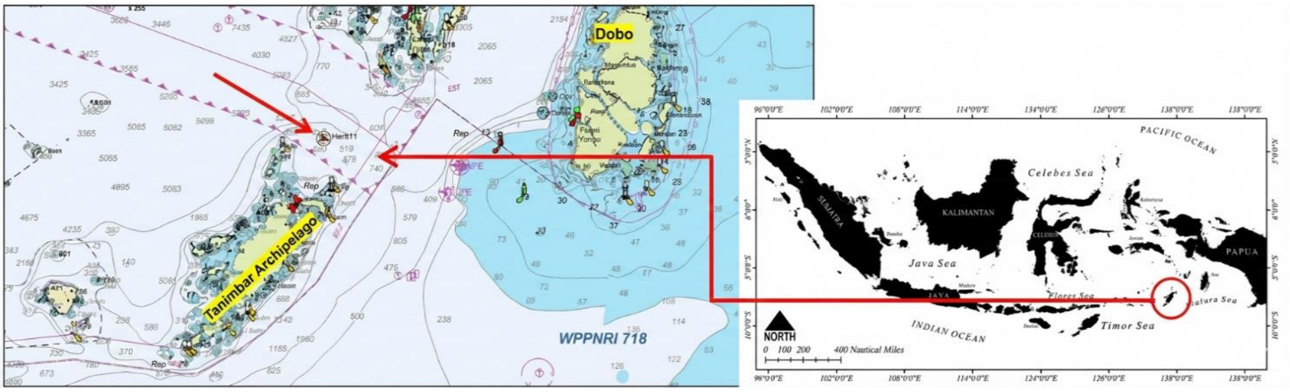

Figure 1. Location of the Hentri-I fire incident (North Tanimbar area, 3 September 2021), used to contextualize offshore operating constraints and potential implications for detection, response, and rescue latency

2.2 Bow-Tie construction, barrier coding, and prioritization

Bow-Tie was constructed around the top event "uncontrolled engine-room fire." Threats, escalation factors, and consequences were extracted strictly from the official investigation narrative and documented vessel arrangements. Barrier extraction from the KNKT narrative followed a systematic protocol: First, the investigation report was reviewed to identify all documented equipment, systems, and procedures relevant to fire prevention, detection, suppression, and emergency response. Second, survivor statements were analyzed for operational practices and equipment usage patterns. Third, vessel arrangement drawings and technical specifications were examined to confirm physical configurations. Barriers were then mapped to the Bow-Tie framework by matching documented elements to their intended safety functions (e.g., fuel-line material specifications were mapped to prevention barriers, portable extinguishers to suppression barriers). This extraction protocol ensures transparency in how case evidence was transformed into the analytical model.

Barriers were classified into four functional layers: prevention (fuel/heat source control and housekeeping), detection (alarm and situational awareness), suppression (attack capability and fixed/portable systems), and consequence management (isolation, communication, evacuation/survival). Each barrier was coded as Present/Absent and, where present, as Effective/Degraded based on report-supported evidence (arrangements, survivor statements, and stated equipment availability). The coding logic operated as follows: "Present" was assigned when equipment, procedures, or physical arrangements were explicitly documented in the KNKT investigation report, vessel specifications, or survivor testimony. "Absent" indicated that the report explicitly stated non-installation or unavailability. For barriers coded as Present, "Effective" required documented functionality without reported failures or reliability concerns, while "Degraded" indicated partial function, maintenance deficiencies, or design limitations that reduced barrier reliability. For example, portable fire extinguishers were coded Present/Effective because they were documented as onboard and accessible, whereas fire detection was coded Absent due to explicit statement of no detector installation. This systematic approach ensures that barrier assessments remain evidence-bounded rather than assumption-driven. Retrofit options were generated by mapping failed/absent barriers to practical engineering actions and ranked using a simple priority logic: (i) impact on preserving response time-window, (ii) feasibility for non-class operators (cost/complexity/maintenance), and (iii) compatibility with wooden-vessel constraints.

3. RESULTS

3.1 Case and vessel baseline relevant to fire-safety barriers

The investigated accident involved Hentri-I, an Indonesian-flagged wooden fishing vessel (bouke ami) built in 2000, with principal particulars of approximately 29.60 m length, 9.12 m breadth, 3.2 m depth, and 195 GT, operating as a non-class vessel. The event culminated in severe fire damage and a presumed sinking; search operations ended without locating the wreck, with 26 persons reported missing and five survivors rescued after hours adrift near the still-burning hull remnant.

The accident narrative provides an outcome-focused dataset suitable for barrier-based results: the ignition source could not be confirmed due to loss of physical evidence, yet multiple design and equipment conditions were documented as creating a high-risk engine-room environment where portable extinguishers alone were insufficient for mitigation. A general view and baseline profile of the non-class wooden vessel are provided in Figure 2, supporting interpretation of compartment arrangement and the practical constraints of machinery-space access during an emergency.

Key technical specifications and the operational context relevant to fire-risk characterization—particularly endurance, manning, and onboard systems—are consolidated in Table 1 to ground subsequent barrier mapping in documented vessel attributes rather than assumptions.

Figure 2. General view and baseline profile of Hentri-I (wooden, non-class fishing vessel)

Table 1. Technical specifications and operational context of Hentri-I relevant to fire risk characterization.

Technical Specification	Documented Condition	Fire-Safety Implication
Vessel construction	wooden hull and superstructure, non-class operation	combustible structural material; no fire-resistant treatment documented
Propulsion system	land-based diesel engine adapted for marine use; modified cooling arrangement; reported temperature ~90 °C	elevated thermal stress; potential ignition source in fuel/oil leak scenarios
Fuel system	fiberglass fuel tank; PVC fuel hoses with clamp connections	heat-vulnerable components; increased leak/ignition risk
Ventilation	natural ventilation without closure capability	oxygen supply cannot be isolated during fire
Fire detection	no detector system installed	delayed recognition; crew dependent on sensory awareness
Fire suppression	four portable extinguishers; no fire pump or fixed system	limited sustained firefighting capability
Emergency communications	no EPIRB or emergency locator beacon	delayed distress alerting; rescue coordination constrained

3.2 Prevention barrier status and initiating conditions in the engine-room system

The investigation record indicates that the vessel operated a land-based diesel engine adapted for marine use with a modified cooling arrangement, and the crew observed fresh-water cooler temperature reaching approximately 90 °C during operation. While specific ignition temperature thresholds for machinery-space scenarios vary with fuel type and release geometry, temperatures approaching or exceeding 90 °C represent elevated thermal stress that may reduce safety margins when hot surfaces coexist with flammable vapors or liquid fuels [1, 7]. In barrier terms, this evidence supports a prevention-side risk state characterized by sustained thermal loading, where deviations in cooling performance can materially increase the likelihood that hot surfaces become effective ignition contributors when combined with fuel or oil releases [1, 7]. Survivor accounts in the investigation record describe a fiberglass fuel tank and PVC hoses used for fuel transfer secured with clamps. The same record notes that wood can absorb oil, increasing combustibility and sustaining burning once heated. These observations support a high-consequence threat condition consistent with machinery-space fire literature, where flammable releases interacting with hot surfaces can initiate rapid fire growth and spread [7].

The documented engine-room hazard landscape is summarized in Table 2, which collates ignition-relevant sources and contributing materials reported in the investigation record. Presenting these elements in a structured inventory supports the prevention-side interpretation of the Bow-Tie by clarifying how heat sources, combustible materials, and fuel-system vulnerabilities can co-exist in a confined wooden machinery space under routine operating conditions.

3.3 Ventilation design as an escalation pathway and a failed isolation barrier

The engine-room ventilation arrangement functioned as an escalation pathway because airflow could not be rapidly isolated once smoke/flame developed. As summarized in Table 3, the vessel relied on natural ventilation openings without effective closure/isolation, enabling oxygen supply and smoke spread that reduced visibility and access for attack.

3.4 Detection barrier absence and implications for response timing

Hentri-I had no fire detector onboard. In the literature on small fishing vessels, detection effectiveness is frequently constrained by limited budgets, harsh maritime environments, and sensor reliability under humidity, salt exposure, and temperature fluctuations [23]. Material selection and compartment design can compound these challenges, making integration of fire-resistant materials and detection systems mutually reinforcing [24]. The results from Hentri-I are therefore unambiguous at the system level: absent detection, the crew's first actionable signal would be human sensory recognition (smoke, smell, heat), which typically occurs later than sensor-based alerts. Recent low-cost fire detection research suggests that dual-stage verification combining rapid sensor triggering with vision-based confirmation can reduce false alarms while preserving prompt alerting and coordinated notification, although the current evidence is derived from controlled indoor settings rather than shipboard environments [9]. This aligns with known early warning failure pathways in maritime contexts where alarms may be absent, unreliable, ignored due to false alarms, or degraded by poor maintenance and training [25]. In this case, the KNKT narrative reports dense white smoke and subsequent visible fire, followed by blackout. These observations suggest that by the time the crew recognized the emergency, the event had already progressed to a stage where power loss and smoke conditions likely constrained response efforts and coordination capability. The detection result is thus framed as a barrier gap with direct operational consequences: delayed recognition compresses the time window in which portable suppression can be effective. The absence of a dedicated detection barrier is carried forward explicitly in the barrier-to-outcome mapping summarized in Table 4, where detection-related deficiencies are treated as a primary contributor to response-time compression. This linkage is used to distinguish evidence-supported timing implications from speculative ignition attribution.

Table 2. Engine-room fire hazard sources and materials as documented for Hentri-I

Engineering Aspect	Observed Condition	Fire-Safety Implication
Engine adaptation	Land-based diesel used in marine environment	Marine-specific thermal and vibration loads may exceed design envelope
Fuel system materials	Fiberglass tank, PVC hoses, mechanical clamps	Degradation under heat/vibration; leak pathways
Structural combustibility	Wood construction without fire-resistant treatment	Accelerated fire growth once ignition occurs
Suppression infrastructure	Portable extinguishers only (no pump/fixed system)	Incipient-fire-only response capability
Ventilation control	Natural airflow without isolation mechanism	Fire escalation cannot be suppressed through oxygen management
Emergency alerting	No EPIRB or beacon installed	External rescue dependent on third-party observation
Regulatory coverage	NCVS lacks detailed fire engineering requirements	Barrier deficiencies not systematically addressed by inspection regime

Table 3. Comparison of Hentri-I fire-related arrangements against cited international voluntary guidance for ventilation isolation and compartment protection

Safety Aspect	International Guidance (FAO/ILO)	Hentri-I Condition	Compliance Gap
Engine-room insulation	fire-resistant boundaries recommended for wooden vessels	wooden structures without fire-resistant lining	non-compliant
Ventilation system	independent and closable ventilation required	ventilation could not be closed	non-compliant
Fuel piping	heat-resistant oil pipes recommended	PVC fuel hoses used	non-compliant
Fire suppression	at least one mechanical fire pump required	no fire pump installed	non-compliant
Fire detection	detection systems implied as essential	no fire detector	non-compliant
Emergency alert	distress alert systems recommended	no locator beacon	non-compliant

Table 4. Engineering implications and barrier-to-outcome linkages derived from the Hentri-I case evidence

Barrier System	Retrofit Action	Engineering Rationale	Measurable Safety Impact
Prevention (Fuel)	replace PVC hoses with heat-resistant metal-braided lines	reduces leak probability under thermal stress	lower ignition likelihood; reduced fuel-fed fire growth
Prevention (Heat)	install thermal shielding on exhaust surfaces; verify cooling system capacity	reduces hot-surface ignition sources	lower probability of ignition from contact with leaked fuel/oil
Detection	install smoke and heat detectors with battery backup	enables early warning before crew sensory recognition	increases available response time by 2-5 minutes (typical sensor-to-recognition interval)
Suppression (Portable)	upgrade extinguisher capacity and accessibility; train crew on agent selection	improves first-line attack effectiveness	higher probability of incipient-fire control
Suppression (Active)	install mechanical fire pump with hose reel	provides sustained water application when portable capacity is exceeded	maintains attack capability during visibility/heat escalation
Escalation Control	add manual closure dampers to ventilation intakes	enables oxygen isolation during fire	limits fire intensity and smoke spread; preserves attack access
Compartment Integrity	apply fire-resistant liner to wooden engine-room boundaries	delays structural involvement in fire	increases structural survivability; extends escape/attack window
Emergency Response	install EPIRB and upgrade survival equipment stowage	accelerates distress alert and rescue coordination	reduces rescue latency; improves post-abandonment survival

3.5 Suppression capability limited to portable extinguishers and lack of active firefighting infrastructure

Suppression capability was limited to portable extinguishers without a dedicated fire pump/hose attack capability or a fixed machinery-space system (Figure 3). This configuration reduced sustained cooling/blanketing potential and increased the likelihood of abandonment once the fire exceeded initial incipient scale. Comparative testing in engine-room-like conditions shows that suppression outcomes differ between CO_2 and water mist, with performance shaped by ventilation modes and heat release behavior [12]. Portable extinguishers can be effective as a first-line defense, but their efficacy declines when flames propagate rapidly, heat release rates rise, and access is obstructed by smoke and high temperatures [26]. The KNKT evidence supports precisely this failure mode: the event progressed to a stage where the vessel suffered blackout and the fire could not be controlled; KNKT explicitly states that the engine-room construction and equipment conditions created high risk and that portable extinguishers alone were not sufficient as mitigation.

Fixed systems, by contrast, are designed to deliver rapid compartment-scale agent coverage when crew access is compromised, although they introduce their own design and safety constraints in confined spaces, especially for gaseous agents. Emerging technologies such as aerosol systems can reduce corrosion impacts on electronics and improve suppression reach in enclosed compartments, but their reliability in the marine environment depends on maintenance and testing regimes. In Hentri-I, the results do not allow evaluation of fixed-system performance because none was installed; instead, the absence itself is the key suppression result, interacting with the absent detection barrier and the non-isolable ventilation pathway to reduce the probability of successful manual firefighting.

The onboard firefighting and survival equipment observed in the case is documented in Figure 3, which provides visual confirmation of the portable-only suppression posture and the practical limitations of first-response capability when machinery-space conditions escalate. This evidence supports the interpretation that portable extinguishers functioned as the sole active suppression option, with limited redundancy and no infrastructure to sustain prolonged firefighting once access became unsafe.

Figure 3. Firefighting and survival equipment observed onboard (portable extinguishers and lifebuoy arrangement)

3.6 Emergency communications and survival outcomes as consequence-barrier performance

The consequences of barrier failure are reflected in the survival and rescue narrative. The vessel lacked a locator beacon usable for distress alerting at sea, which constrained the ability to provide immediate position information to search and rescue authorities. The report indicates that accident information reached SAR only after survivors were already evacuated to land by a passing vessel, implying a delay in mobilizing coordinated response resources. In the literature, emergency communication failures increase response times and degrade coordination both onboard and with external responders, particularly when power outages occur and crews over-rely on electronics. Communication breakdowns can also be amplified by procedural complexity, training deficiencies, and stress-induced decision-making errors [27]. The case outcome 26 missing and five survivors demonstrates a catastrophic survival result consistent with scenarios where fire escalation forces abandonment under smoke and heat, while rescue is delayed due to weak distress signaling.

Figure 4. Vessel condition during survivor evacuation, illustrating post-escalation damage consistent with loss of compartment control

Survival equipment accessibility and readiness are well established as determinants of survival probability during rapid-onset emergencies. The report's imagery and equipment inventory confirm the presence of lifebuoys and extinguishers, but the results indicate that equipment presence alone did not prevent mass casualties, reinforcing literature that emphasizes maintenance, drills, and cohesive emergency behavior as essential complements to hardware. In this case, the combination of late detection, inadequate suppression capacity, non-isolable ventilation, and delayed external alerting forms a coherent barrier-failure chain leading to the observed outcome.

Consequence-side evidence is synthesized using Figure 4, which captures the evacuation context and the physical signs consistent with loss of compartment control and severe escalation. To translate this evidence into engineering-actionable inferences, Table 4 summarizes the barrier-to-outcome linkages derived from the case record, showing how prevention, detection, suppression, and consequence-management degradations coherently align with the observed survivability trajectory.

4. DISCUSSION

4.1 Hentri-I as a barrier failure chain rather than an ignition-cause case

Because the ignition source could not be confirmed due to loss of physical evidence, the case is more defensibly treated as a barrier-performance failure chain than as a root-cause attribution study. The outcome severity (26 missing, five survivors) indicates that once onboard control was exceeded, survival depended primarily on late-stage actions under degraded conditions rather than early containment. This is exactly the use-case for Bow-Tie methods, which connect threats to consequences through preventive and recovery barriers while keeping causal claims bounded to evidence [21] and providing a communication tool for complex, multi-factor pathways [22]. This "barrier failure chain" framing is made explicit in Table 4, which consolidates the evidence-bounded links from degraded barriers to observed outcomes and provides a transparent basis for discussing escalation without over-claiming an ignition source. Using the table as the interpretive anchor strengthens internal validity by keeping the discussion aligned with verifiable case elements rather than conjecture.

4.2 Prevention weaknesses and why they matter in wooden engine rooms

The results align with dominant engine-room fire patterns reported for fishing vessels—overheating, leak-prone fuel and oil systems, equipment limitations, and weak maintenance regimes [1]. The documented conditions sustained thermal loading including the reported 90 ℃ cooler temperature alongside a fuel-transfer arrangement using fiberglass tank and PVC hoses are consistent with scenarios in which small fuel leaks or mist releases could interact with hot surfaces to initiate fire development [7]. The wooden compartment context intensifies this risk because oil absorption can increase combustibility and reduce ignition resistance as heating progresses. The combined implication is not a single ignition trigger, but a prevention barrier set that is structurally vulnerable to both initiation and early growth. The prevention weaknesses discussed here should be read alongside Table 1 and Table 2, which together ground the argument in documented vessel context and the recorded hazard sources/materials rather than generalized assumptions about wooden fleets. This coupling supports a defensible claim that prevention gaps are not abstract but embedded in specific, reportable arrangements that plausibly elevate ignition likelihood and early growth potential in the machinery space.

4.3 Ventilation as a primary escalation control that failed by design

As documented in Section 3.3, the ventilation system could not be isolated during fire development, preventing oxygen supply management—a critical escalation-control barrier. This design limitation matters because ventilation and airflow patterns shape compartment ignition thresholds and flame behavior influence whether heat release remains controllable or transitions rapidly to a developed fire [12]. Unmanaged ventilation also promotes smoke accumulation and visibility loss and can increase the risk of abrupt fire growth if air is introduced suddenly. In practical terms, the lack of isolation capability likely removed one of the few low-cost escalation levers available on small vessels once portable suppression became unsafe. The ventilation-centered escalation interpretation is operationalized through Table 3, where the case arrangements are contrasted against guidance emphasizing isolation and compartment integrity as escalation controls. Referencing the table directly clarifies that the argument concerns a barrier-design and barrier-availability deficit, not a retrospective assumption about the precise ignition sequence.

4.4 Portable-only suppression and the collapse of the response window

The results show a brittle suppression system: no fire pump and no fixed suppression, so control depended on portable extinguishers under worsening smoke and heat. This configuration is inherently time-critical because portable extinguishers succeed primarily in early-stage fires and require rapid use, correct agent selection, and crew competence [28]. As heat release increases and access is constrained, portable effectiveness declines [26], and experimental work confirms that suppression performance is strongly affected by ventilation mode. In barrier terms, the absence of an accessible second line of active suppression means that once the first manual attempt fails, escalation probability rises sharply especially when ventilation cannot be isolated and detection is absent.

4.5 Regulatory gaps and the rationale for minimum viable retrofit packages

The case profile fits known regulatory gaps for non-class vessels, where fire safety requirements and enforcement can be inconsistent, leaving major hazards unmanaged. Studies highlight the absence of clear requirements and regular inspections as drivers of inadequate suppression systems and degraded readiness [29]. Strengthening fire safety barriers physical and procedural has been linked to reduced fire spread and improved evacuation performance on small ships. However, small-vessel operators face resource constraints that limit adoption of comprehensive solutions. This supports the practical direction of this paper: prioritize a minimum viable retrofit set that targets barriers most responsible for escalation control. Relevant retrofit evidence supports improving fire resistance of wood [30], adding protective reinforcement approaches, integrating automated/fixed suppression where feasible, improving ventilation performance to reduce hazardous buildup [31, 32], and embedding emergency planning, regular drills, communication discipline, and continuous crew training to ensure that barriers can be activated effectively under stress, since engine-room safety performance is strongly shaped by human factors such as inadequate knowledge, miscommunication, fatigue, and weak safety culture [33].

4.6 Contribution, limitations, and next research steps

This study's contribution is translational: it converts an evidence-limited investigation report into a structured Bow-Tie and barrier performance interpretation that yields engineering-actionable priorities without overstating ignition causality. This matches the broader need for methods that identify weak links and guide feasible remedial actions under real constraints [7, 34]. This study is limited to a single evidence-bounded case based on an investigation report and survivor statements, without instrumented compartment data (temperatures, ventilation flow, or suppression discharge characteristics). Consequently, the findings are intended for barrier prioritization and retrofit direction rather than probabilistic frequency estimation or definitive ignition attribution. Future research should synthesize multiple Indonesian wooden-vessel fire cases to test the stability of barrier rankings and, where data allow, apply performance-based analyses of machinery-space fire scenarios to strengthen design recommendations.

4.7 Barrier interaction framework for small-vessel fire safety

To generalize the Hentri-I findings beyond a single case, Table 5 presents a barrier interaction framework illustrating how prevention, detection, suppression, and consequence-management layers create redundancy and preserve response time-windows. Prevention barriers (fuel-line integrity, heat shielding, maintenance) reduce ignition probability. When prevention fails, detection barriers (sensors, alarms) compress recognition delay and enable early intervention. Suppression barriers (extinguishers, fire pumps, fixed systems) provide graded response capability; degradation at this layer shifts outcomes toward evacuation dependency. Consequence-management barriers (isolation, communications, survival equipment) determine post-escalation survivability. The framework shows that barrier degradation in upper layers (prevention, detection) compresses the effective time-window for lower-layer intervention, while degradation at suppression forces reliance on consequence management alone—precisely the failure chain observed in the Hentri-I case. This structure is transferable to other small-vessel fire scenarios and supports systematic retrofit prioritization by identifying which barrier layers offer maximum time-window preservation per unit investment.

Table 5. Barrier interaction framework for small-vessel fire safety: functional layers, time-window preservation, failure propagation, and Hentri-I case mapping

Barrier Layer	Primary Function	Time Window Preserved	Failure Impact on Downstream Layers	Hentri-I Status	Retrofit Priority
Prevention	Reduce ignition probability through fuel-line integrity, heat shielding, maintenance regimes, and compartment boundaries	Pre-ignition window: Extends time before fire threat emerges; determines initial conditions for detection and suppression	When degraded/failed: Increases ignition likelihood; shifts burden to detection with compressed response time; creates high-consequence initial conditions (fuel-fed, high heat release)	DEGRADED: PVC fuel lines vulnerable to thermal stress; 90 °C cooler temperature; wooden boundaries without fire-resistant treatment; sustained thermal loading	Priority 1 (High Impact, Low Cost): Replace PVC fuel lines with heat-resistant metal-braided hoses; install thermal shielding; verify cooling system capacity
Detection	Compress recognition delay through smoke/heat sensors, alarm systems, early warning, and crew awareness	Recognition window: 2-5 minutes typical sensor-to-crew interval; enables suppression engagement while conditions remain tenable	When absent/delayed: Eliminates early warning; forces suppression to operate reactively under smoke, heat, and visibility constraints; compresses suppression time-window to minutes or seconds	ABSENT: No fire detector system installed; crew dependent on sensory awareness only; recognition occurred after smoke/flame propagation, blackout imminent	Priority 1 (High Impact, Low Cost): Install smoke and heat detectors with battery backup; minimal cost, maximum time-window preservation
Suppression	Control fire development through portable extinguishers, fire pumps, fixed CO_2/water-mist systems, and ventilation isolation	Attack window: Minutes to tens of minutes if detection enables early engagement; seconds if detection absent; determines whether fire is controlled onboard or escalates to evacuation	When limited/exceeded: Exhausts onboard firefighting capability; forces immediate reliance on consequence management (evacuation, external rescue); outcome determined entirely by survival equipment and rescue latency	LIMITED: Portable extinguishers only (4 units); no fire pump or fixed suppression system; natural ventilation without isolation capability; incipient-fire-only response capacity	Priority 2 (Moderate Investment): Install mechanical fire pump with hose reel; add manual ventilation closure dampers; provides sustained attack capability when portable capacity exceeded
Consequence Management	Determine post-escalation survivability through emergency communications (EPIRB), evacuation procedures, and survival equipment	Survival window: Hours to days depending on distress alert speed, rescue coordination, and offshore conditions; only engaged when all upstream barriers fail	When weak/delayed: Prolongs rescue latency; increases exposure to offshore hazards (hypothermia, drowning, dehydration); catastrophic outcome probability rises sharply with each hour of delay	WEAK: No EPIRB or emergency locator beacon; distress alert reached SAR only after survivors evacuated by passing vessel; rescue coordination delayed; outcome: 26 missing, 5 survivors	Priority 2 (Moderate Investment): Install EPIRB for immediate distress alerting; upgrade survival equipment stowage and accessibility; accelerates rescue coordination

5. CONCLUSION

This study reframed the Hentri-I engine-room fire as a barrier-performance problem and showed how multiple small deficiencies can interact to produce catastrophic outcomes on non-class wooden fishing vessels. The evidence indicates a prevention profile dominated by sustained heat stress and fuel-system vulnerability, while escalation was accelerated by three missing or weak barriers: early detection, ventilation isolation, and effective compartment-level suppression. With suppression limited to portable extinguishers, the response window narrowed rapidly, and survivability shifted toward evacuation and external rescue. These findings support a practical implication: minimum viable fire safety for offshore wooden vessels should prioritize barriers that buy time through a phased retrofit approach. Priority 1 (High Impact, Low Cost, Immediate Feasibility): Replace PVC fuel hoses with heat-resistant metal-braided lines, install manual ventilation closure dampers on natural air intakes, deploy basic smoke/heat detectors with battery backup, and upgrade portable extinguisher capacity with crew training. These measures directly address the most critical barrier gaps with minimal vessel downtime and capital investment. Priority 2 (Moderate Investment, Substantial Capability Improvement): Install a dedicated fire pump with hose reel for sustained machinery-space attack, add fire-resistant liner panels to wooden engine-room boundaries, and integrate an emergency position-indicating radio beacon (EPIRB) for distress alerting. Priority 3 (Higher Complexity, Maximum Protection): Implement a fixed CO_2 or water-mist suppression system for machinery spaces and establish formal pre-departure inspection and maintenance protocols enforced through logbook verification. Recognizing the economic constraints of small-scale operators, Priority 1 measures can be implemented with locally available materials and minimal technical expertise, while Priorities 2-3 require phased investment aligned with fleet renewal or regulatory modernization cycles.

The scientific contribution is an actionable, case-to-model translation that links investigation evidence to an explicit Bow-Tie barrier structure and retrofit prioritization, offering a pathway for risk reduction without large datasets. Future work should validate the proposed retrofit package using scenario-based performance modelling (e.g., ventilation and suppression sensitivity) and extend the barrier coding approach across additional fire cases to quantify uncertainty, compare fleet segments, and inform proportionate regulatory requirements for small fishing vessels.

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