Indoor Air Quality Measurement Onboard Royal Malaysian Navy Warship: Implication for Crew Stress Level

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ABSTRACT

Indoor Air Quality (IAQ) is a critical determinant of health, operational performance, and psychological well-being, particularly in enclosed and high-risk maritime environments such as warships. This study examines IAQ conditions onboard KD JEBAT, a Royal Malaysian Navy frigate, and their implications for crew stress levels. Five IAQ parameters, carbon dioxide (CO_2), carbon monoxide (CO), relative humidity, temperature, and air movement were systematically monitored using a calibrated IAQ multifunction data logger across four mission-critical compartments: the Galley, Combat Information Center (CIC), Bridge, and Machinery Control System Room (MCSR). Data were collected over an 8-hour surrogate duration, segmented into four operational time slots, and benchmarked against the Industry Code of Practice on Indoor Air Quality (ICOP 2010). Measurements were further contextualized against crew occupancy patterns, task intensity, and compartment functions. Finding of IAQ assessments revealed CO_2 exceedances in CIC and MCSR, low wind speeds in all compartments, and thermal discomfort across sections highlighting stress related conditions to ventilation and temperature imbalances. These environmental stressors were closely associated with cognitive fatigue, physiological strain, and reduced situational awareness. The study underscores the importance of continuous IAQ monitoring, demand-responsive ventilation, and human-centered engineering strategies to mitigate occupational stress. The outcomes offer practical and policy-level insights aligned with Environmental, Social, and Governance (ESG) principles, the United Nations Sustainable Development Goals (SDGs), and Malaysia MADANI priorities for defense infrastructure.

Keywords: Indoor Air Quality, Crew Stress, Warship Environment, Royal Malaysian Navy.

INTRODUCTION

Indoor Air Quality (IAQ) is increasingly recognized as a critical factor affecting the health, cognitive performance, and operational effectiveness of personnel operating in enclosed and high-stress environments. In the context of naval operations, warships present unique IAQ challenges due to their sealed compartments, prolonged deployment durations, high crew density, and limited natural ventilation. These conditions can lead to the accumulation of airborne pollutants, excessive carbon dioxide (CO_2), fluctuating humidity, and thermal discomfort all of which may compromise crew performance, endurance, and well-being (Liu, 2023; Zhou, 2021).Despite growing international attention to IAQ within built environments, empirical investigations focused on naval maritime platforms remain limited. Most prior research has concentrated on land-based or civilian transport systems, such as aircraft cabins, railway coaches, and cruise ships (Van Tran & Lee, 2020; McGill & Musau, 2020; Metreveli, 2020). In contrast, the warship environment despite its operational complexity and strategic significance has received comparatively less scrutiny (Kim & Lee, 2010). Existing IAQ studies related to naval platforms often adopt differing methodological frameworks, use non-standard measurement criteria, or lack correlation with human performance indicators (Zahaba, 2022).

Within the Malaysian defence context, Zahaba (2022) conducted a preliminary investigation of IAQ onboard a Royal Malaysian Navy (RMN) warship. However, the study was limited to only six sample points and did not explore the relationship between IAQ conditions and crew psychological responses. The potential link between environmental quality and occupational stress particularly in enclosed military workspaces remains a key knowledge gap. Cooper (2021) earlier emphasized that environmental stressors, such as poor air quality, can amplify psychological strain among personnel. Yet, few empirical studies have attempted to quantify this interaction within naval architecture.This gap is particularly significant when viewed through the lens of the United Nations Sustainable Development Goals (SDG 2015) especially SDG 3 (Good Health and Well-Being) and SDG 8 (Decent Work and Economic Growth) as well as through the Environmental, Social, and Governance (ESG) framework increasingly adopted in modern defence asset planning. Ensuring acceptable IAQ levels aboard warships is not only a matter of compliance but a matter of strategic health protection and mission assurance.

Accordingly, this study aims to assess IAQ conditions in four mission critical compartments onboard an RMN warship which is Galley, Bridge, Main Communication Station Room (MCSR), and Combat Information Centre (CIC). Real-time measurements carbon dioxide (CO_2), carbon monoxide (CO), temperature, relative humidity, and air movement were conducted using calibrated instruments, and benchmarked against the Industry Code of Practice on Indoor Air Quality (ICOP 2010) issued by the Department of Occupational Safety and Health (DOSH), Malaysia. The findings are critically analyzed to evaluate operational vulnerabilities associated with IAQ and its psychophysiological impact on crew stress, thereby may establish empirical foundations for future maritime habitability standards and shipboard environmental design enhancement.

METHODOLOGY

To systematically assess IAQ onboard KD JEBAT, a preliminary study was first conducted to identify the most suitable compartments for measurement. All measurements were conducted in accordance with the ICOP 2010 issued by the DOSH Malaysia, focusing on both indoor air contaminants (CO and CO_2) and physical parameters (humidity, temperature, air movement). Sampling followed ICOP 2010 protocols, with each compartment monitored using a Multifunction Data Logger strategically placed according to standard spatial criteria, including distance from walls, airflow sources, and traffic zones. Data collection was performed from 2 to 7 January 2024, using intermittent monitoring over standard working hours. ICOP compliant methodology enabled accurate and operationally relevant evaluation of IAQ across mission critical compartments onboard the vessel.

Site Selection

The site selection for this study was guided by four principal factors: ship characteristics, crew size, logistical feasibility, and flagship status. Vessels were prioritized based on their structural configuration and operational functions, which align with the technical requirements of IAQ assessments (Harris, 2017). A minimum onboard crew size exceeding 100 personnel was deemed essential to ensure data representativeness and meet methodological standards for research validity (Bailey, 2016). Logistical constraints such as cost, time, and geographical accessibility also shaped feasibility, with the selection favouring ships available within the researcher’s proximity to minimize resource expenditures. Furthermore, the ship’s designation as the Royal Malaysian Navy’s (RMN) flagship enhanced its strategic significance and institutional relevance, thereby strengthening the generalizability and impact of the study’s findings (Merriam, 2021). Given that the RMN operates a fleet of over 50 active warships of varying classes and configurations, several strategic criteria were established to determine the most appropriate vessel for the study. These criteria included crew complement size, ship characteristic, flagship of RMN, and researcher preference (cost, time and location). Based on these factors, KD JEBAT (Figure 1) a front line multi role frigate was selected as the study platform due to its representativeness of flagship, technical complexity, and accessibility to the researcher for structured observation.

Figure 1: KD JEBAT
Source: Lt Rozaireen (2020)

Preliminary Study for Compartment Selection

A preliminary study was conducted to identify the most appropriate compartments onboard KD JEBAT for conducting IAQ measurements. As highlighted by Preliminary (2020), such studies are critical for refining trial procedures and ensuring effective planning for data collection. Given that KD JEBAT contains over 100 compartments, this preliminary phase was essential to strategically narrow down the selection to spaces that are operationally significant and potentially prone to air quality issues due to high occupancy or pollutant sources. The primary objective was to identify compartments with high crew activity, potential pollutant emissions, and a balanced representation of operational, working, and living areas. This targeted approach ensured that IAQ assessments would focus on areas most relevant to mission performance and crew well-being. To support this effort, a structured survey was administered to 30 crew members from various departments, who were asked to rate the suitability of different compartments using a 1-to-10 Likert scale, with higher scores indicating greater relevance for IAQ monitoring. The sample size follows the guidance of Hertzog (2008), who recommended 10 to 30 participants for preliminary studies aimed at estimating variability or refining research procedures.

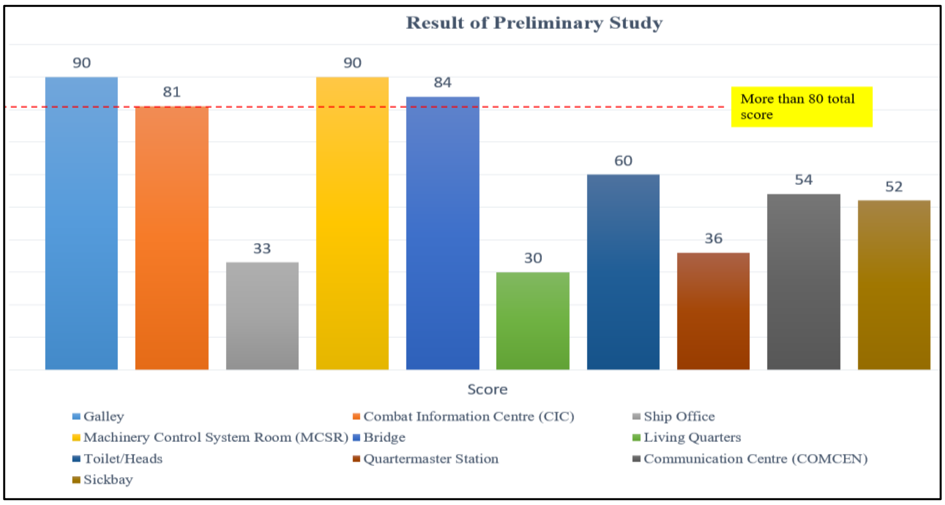

Figure 2 – Result of Preliminary Study

Refer to Figure 2, Galley and MCSR received the highest total scores (90), indicating their criticality in terms of potential pollutant generation and equipment related emissions. The CIC and Bridge followed closely with scores of 81 and 84, reflecting their importance in terms of crew presence and operational activities. Conversely, compartments such as the Ship Office, Living Quarters, and Quartermaster Station received lower scores, suggesting they were of lower priority for initial IAQ monitoring. In line with the Pareto Principle (1991), which posits that 80% of consequences arise from 20% of causes the results guided the selection of four compartments (Galley, MCSR, CIC, and Bridge) for detailed IAQ monitoring in the subsequent phase of the study. These spaces represent a cross section of operational, technical, and environmental characteristics, thus ensuring a comprehensive assessment of shipboard air quality.

Table 1: Table for Indoor Concentration based on ICOP

Parameter	ICOP 2010	Equipment
Indoor Air Contaminant		
CO	10 ppm	Multifunction Data Logger
CO_2	1000 ppm	Multifunction Data Logger
Physical Parameter		
Relative Humidity	40-70%	Multifunction Data Logger
Air Temperature	23-26^0 C	Multifunction Data Logger
Ventilation Rate (VR)/ Air Movement	0.15-0.50m/s	Multifunction Data Logger

Source: Kim and Lee, 2016

IAQ Measurement and Compliance with ICOP 2010

The ICOP provides standardized guidelines for acceptable indoor concentration levels of specific contaminants and environmental conditions to safeguard occupant health, particularly in enclosed or sealed environments such as naval vessels. The IAQ measurement focused on two key categories (a) Indoor Air Contaminants (b) Physical Parameters. As outlined in Table 1, the recommended threshold for carbon monoxide (CO) is 10 parts per million (ppm), while carbon dioxide (CO_2) should not exceed 1000 ppm. For physical parameters, ICOP 2010 recommends maintaining relative humidity between 40% and 70%, air temperature between 23°C and 26°C, and ventilation rate or air movement within the range of 0.15 to 0.50 meters per second (m/s). All parameters were monitored using a Multifunction Data Logger Delta OHM HD37AB1247 (Figure 3) integrated with directional hotwire probe and IAQ probe which enabling real-time tracking and data logging of each parameter at the designated sample points. These instruments were selected based on their precision, portability, and compliance with occupational health standards (Kim & Lee, 2016). This ICOP based framework serves as the benchmark for evaluating the IAQ conditions onboard KD JEBAT.

Figure 3: Multifunction Data Logger

Sampling Duration and Intervals

In accordance with ICOP 2010 (Para A4.2.3), the standard sampling period is based on an eight-hour workday to reflect typical occupational exposure. Due to operational constraints onboard naval platforms, a pragmatic intermittent sampling approach was adopted. This involved four staggered 30-minute measurement sessions throughout the day, capturing diurnal fluctuations in air quality while respecting shipboard routines and field constraints.

Placement and Criteria of Sampling Points

The number of sampling points was determined based on the size, function, and layout of each compartment (ICOP, 2010, Para A4.2.2). Since each compartment had a floor area below 3000 m² and was fully serviced by

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mechanical ventilation and air-conditioning (MVAC), one sampling point per compartment was sufficient (ICOP, 2010). Sampling devices were deployed using a spatial strategy to ensure full coverage of occupancy zones. Real-time data loggers were positioned at designated points that met ICOP requirements for accurate and unbiased measurement. The ICOP protocol outlines specific guidelines to optimize the accuracy of IAQ measurements:

- Representing Workstation Layouts: Samplers were placed to reflect real occupant exposure during operational duties (ICOP, Para A4.2.2a).
- Minimal Disruption: Locations were selected to avoid interference with crew activity (ICOP, Para A4.2.2b).
- Distance from Vertical Surfaces: At least 0.5 meters from walls, corners, or obstructions (ICOP, Para A4.2.2c).
- Avoidance of Airflow Obstruction: Not placed in front of fans, vents, or heat sources (ICOP, Para A4.2.2d).
- Shielding from Direct Sunlight: To prevent sensor distortion (ICOP, Para A4.2.2f).
- Away from Pathways and Equipment: Not in corridors or near printers/copiers (ICOP, Para A4.2.2g).
- Spatial Awareness: Avoided proximity to elevators and entrances (ICOP, Para A4.2.2i).
- Safety Consideration: No obstruction to emergency exits or movement routes (ICOP, Para A4.2.2j).
- Sampling Height: Sampler inlets positioned between 75 cm and 120 cm, ideally at 110 cm to reflect the human breathing zone (ICOP, Para A4.2.2l).

IAQ Fieldwork Measurement Setup

Measurements were conducted using multifunction data loggers, set up in accordance with the ICOP 2010 issued by DOSH Malaysia. All fieldwork was carried out between 2 - 7 January 2024, from 0800 to 1700 hours, aligning with the crew's active duty period. Refer to Figure 3 for location of four mission critical compartment. In all locations, sampling points were strategically located at least 0.5 meters from walls and vertical surfaces, 2 meters from doors, and outside of pathways and direct sunlight exposure. Samplers were positioned at 110 cm from the floor, within the ICOP's recommended range of 75–120 cm, to reflect typical human breathing levels. The setup ensured accurate, standardized, and compliant IAQ measurements representing real-world crew exposure in key operational areas. Details of location description and floor plan of each compartment as elaborate in Table 2.

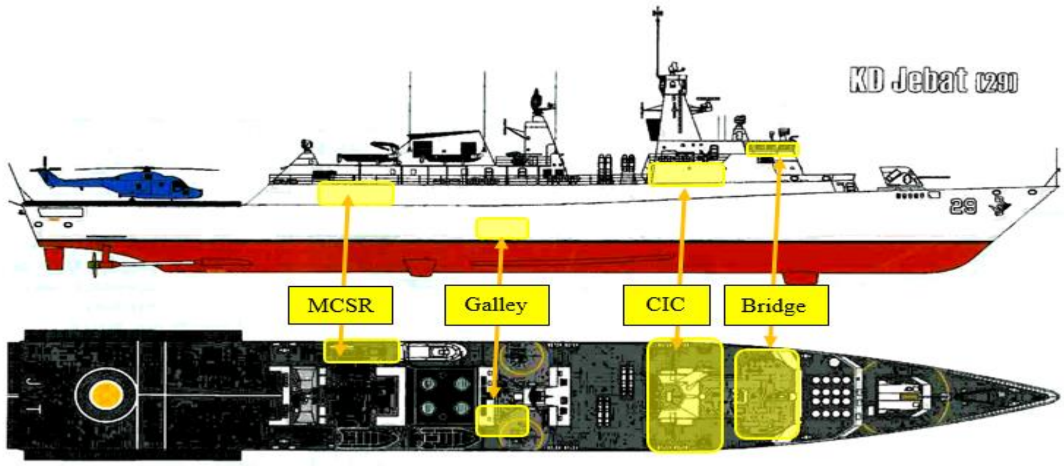

Figure 3: Location of Compartment IAQ Fieldwork Measurement

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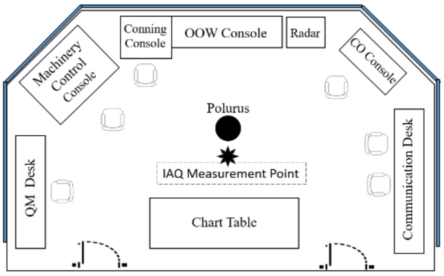
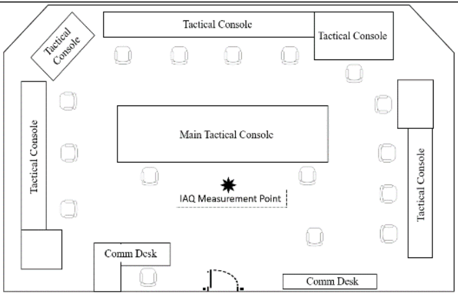
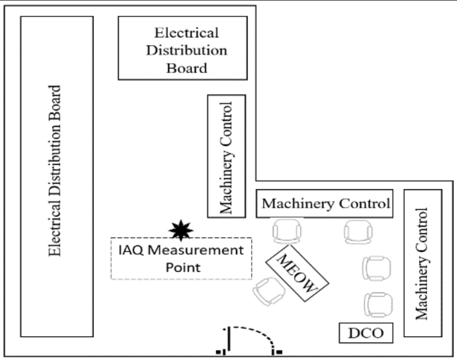
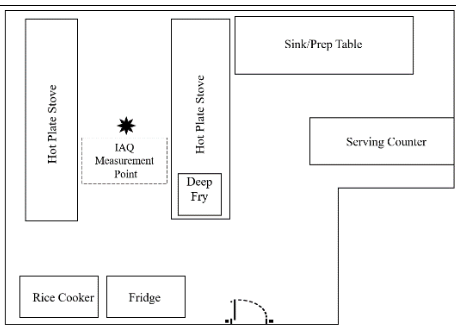
Table 2: Floor Plan and Description

Related Picture	Floor Plan of Compartment	Location Description
		**Bridge** (55 m²): navigational purpose required constant crew alertness. The monitor was installed near the central polurus, away from airflow sources and at 110 cm height (average breathing zone) Date: 7th January 2024
		**CIC** (120 m²): main operational center, hosts continuous personnel activity and heat from electronic systems. The device was placed at a main workstation (PWO Console), positioned at seated shoulder height. Date: 3rd January 2024
		**MCSR** (30 m²): critical machinery control subject to elevated heat and humidity. The monitor was installed at the crew's primary monitoring station, maintaining a minimum distance from walls, vents, and doors to ensure valid readings. Date: 6th January 2024
		**Galley** (80 m²): Know as kitchen for ship, subject to thermal load and airborne particulates. The sampling point placed away from high-traffic areas, heat sources, and ventilation outlets, also at the standard breathing zone height. Date: 2nd January 2024

RESULT

IAQ assessments onboard KD JEBAT demonstrated varying degrees of compliance with ICOP 2010 across four mission critical compartments which is Galley, CIC, Bridge, and MCSR. As illustrated in Table 3 and Table 4, the results indicate that while parameters such as CO_2, CO, relative humidity, air movement, and temperature generally fell within acceptable thresholds in certain compartments. These findings highlight deficiencies in ventilation and thermal regulation that may affect crew stress and performance. A detailed analysis of IAQ result by compartment is presented in the subsequent subchapters.

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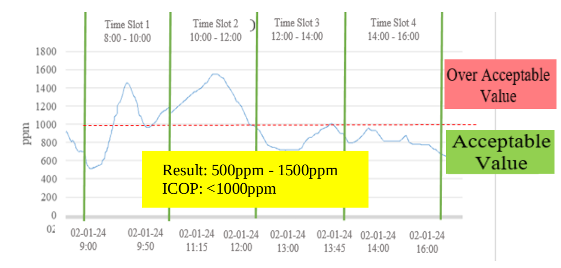
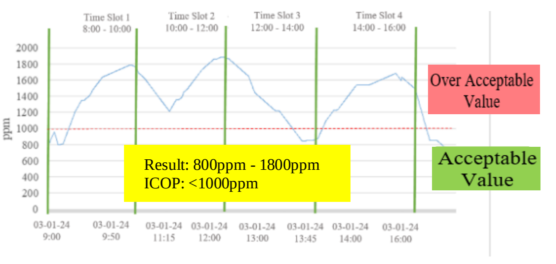
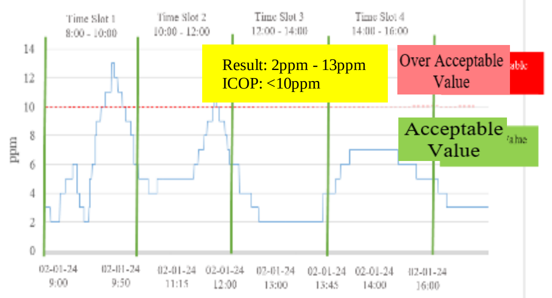
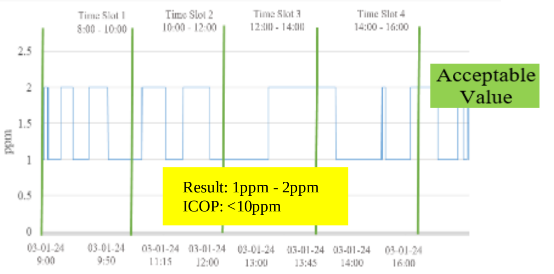
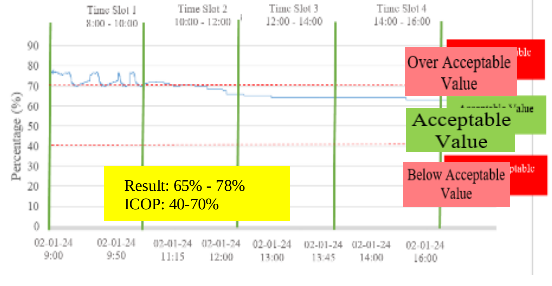
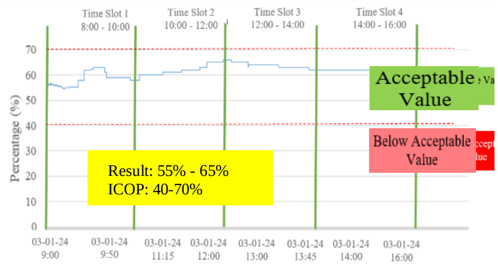
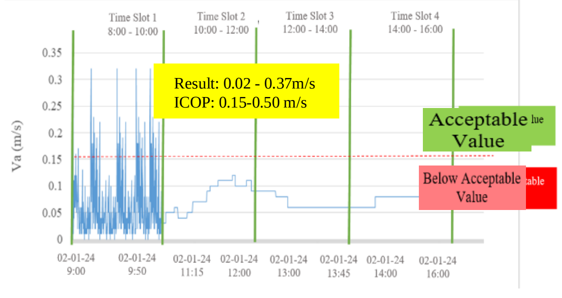
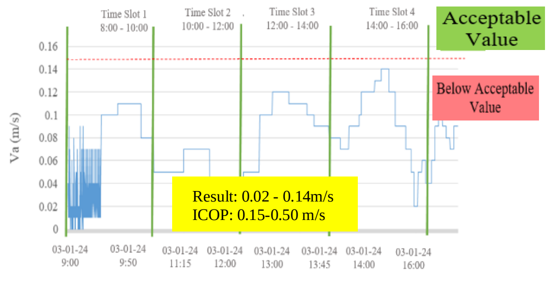
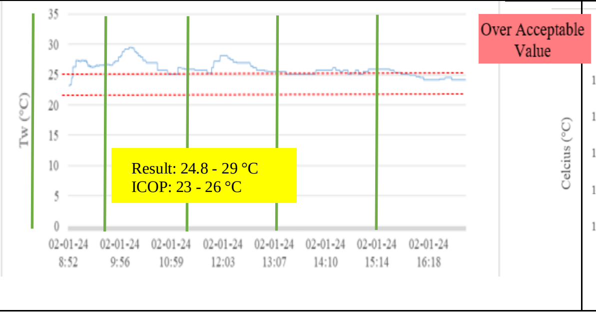
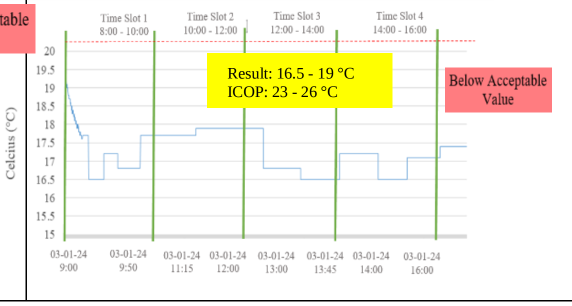
Table 3: Result of IAQ Measurement for Galley and CIC

<table>
<tr><th></th><th>Galley</th><th>CIC</th></tr>
<tr><td>CO_2 (ppm)</td><td>
</td><td>
</td></tr>
<tr><td>CO ppm</td><td>
</td><td>
</td></tr>
<tr><td>RH (%)</td><td>
</td><td>
</td></tr>
<tr><td>Speed (m/s)</td><td>
</td><td>
</td></tr>
<tr><td>Temp °C</td><td>
</td><td>
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</table>

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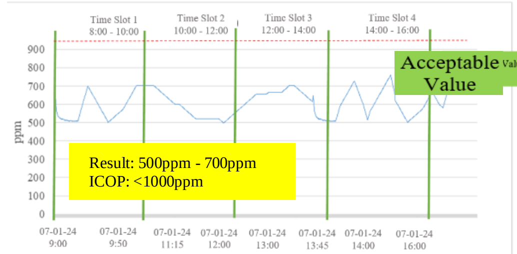
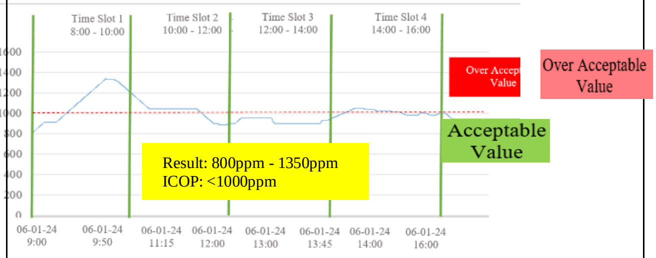
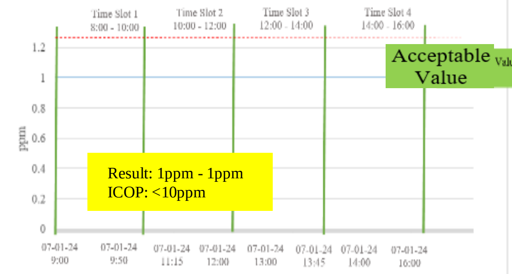
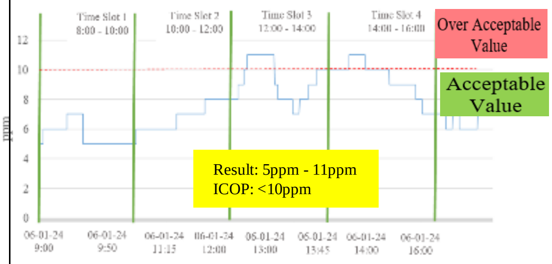
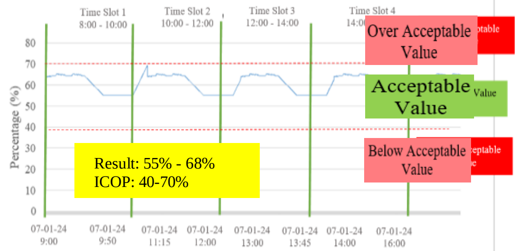
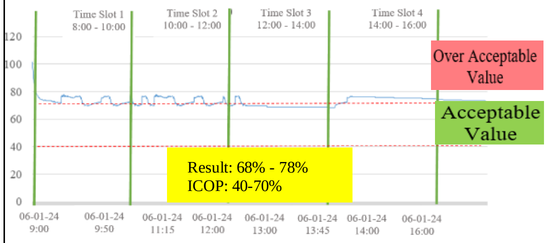
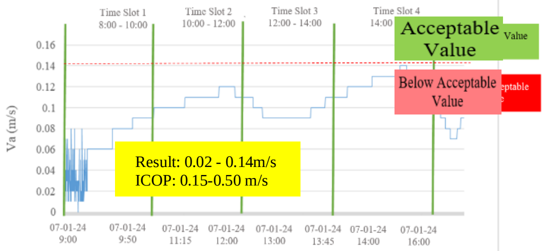
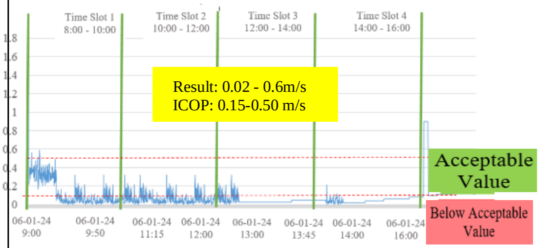
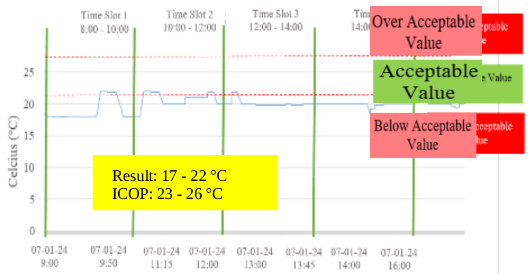
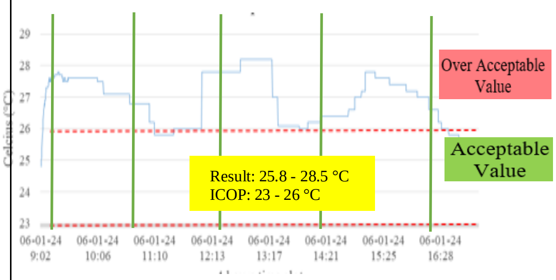
Table 4: Result of IAQ Measurement for Bridge and MCSR

	Bridge	MCSR
CO_2 (ppm)		
CO ppm		
RH (%)		
Speed (m/s)		
Temp °C		

Galley

The IAQ assessment at the galley reveals several non-compliances with the ICOP. CO_2 levels peaked at 1500 ppm, exceeding the ICOP threshold of <1000 ppm during Time Slot 1 and 2, indicating inadequate ventilation (DOSH, 2010). CO levels ranged between 2–13 ppm, surpassing the ICOP limit of <10 ppm in multiple intervals, especially Time Slot 1 and 2, suggesting potential combustion sources. Relative Humidity (RH) fluctuated between 65%–78%, where values above 70% exceeded the acceptable range (40%–70%), risking discomfort and mold growth. Air movement showed velocities between 0.02–0.37 m/s; although within the ICOP range (0.15–0.50 m/s) during parts of the day, values in Time Slot 1 and early Slot 2 were mostly below the minimum limit. Lastly, temperatures were recorded between 24.8°C–29°C, with readings above the ICOP limit of 26°C in all time slots, indicating thermal discomfort. These deviations collectively suggest the need for improved ventilation and temperature control (Zuraimi & Tham, 2008).

Combat Information Center (CIC)

The IAQ analysis at the CIC reveals critical deviations from ICOP (DOSH, 2010). CO_2 concentrations ranged from 800–1800 ppm, exceeding the <1000 ppm ICOP limit during all time slots, especially between 08:00–14:00 (Time slot 1 until 3), indicating inadequate ventilation in a high-occupancy, enclosed space. CO levels remained within acceptable limits (1–2 ppm vs. <10 ppm), suggesting minimal combustion-related risks. However, air movement was insufficient, recorded between 0.02–0.14 m/s, falling short of the 0.15–0.50 m/s threshold, which may reduce thermal comfort and airflow effectiveness. Relative humidity remained within the acceptable 40%–70% range, registering 55%–65%, supporting equipment reliability and human comfort. The most concerning variable was ambient temperature, which fell between 16.5°C–19°C, far below the ICOP standard of 23°C–26°C. Prolonged exposure to such low temperatures could impair personnel alertness and cognitive performance in a mission-critical environment (Lan et al., 2011). These findings emphasize the urgent need to enhance ventilation and recalibrate HVAC settings for thermal adequacy and operational efficiency.

Bridge

The IAQ results on the Bridge of KD JEBAT indicate generally acceptable air quality, with minor thermal and ventilation concerns. CO_2 levels remained within ICOP limits (<1000 ppm), ranging between 500–700 ppm throughout all time slots, reflecting adequate ventilation (DOSH, 2010). CO levels were stable at 1 ppm, well below the 10 ppm threshold, indicating negligible combustion exposure. Relative humidity varied from 55%–68%, which, although within ICOP's 40%–70% range, trended near the upper limit, which may affect comfort over prolonged periods. Air movement was subpar, fluctuating between 0.02–0.14 m/s below the recommended 0.15–0.50 m/s except for slight improvements during Time Slot 4, suggesting inadequate air circulation during most periods. Temperature readings ranged from 17°C–22°C, consistently below the ICOP range (23°C–26°C). Prolonged exposure to these lower temperatures may compromise crew performance, especially in critical navigation roles (Lan et al., 2011). In conclusion, while gas concentrations were within safe limits, suboptimal ventilation and undercooling highlight the need for HVAC adjustments to meet thermal comfort and operational efficiency standards.

Machinery Control System Room (MCSR)

IAQ monitoring at the MCSR revealed several non-compliances with ICOP standards. CO_2 levels ranged from 800–1350 ppm, breaching the 1000 ppm limit during Time Slots 1, indicating inadequate ventilation during peak occupancy (DOSH, 2010). Carbon monoxide (CO) levels were generally within the <10 ppm limit but peaked at 11 ppm in Time Slot 3, suggesting a brief emission source or ventilation lapse. Relative humidity fluctuated between 68–78%, slightly exceeding the 70% threshold, which could lead to discomfort or microbial growth risks. Air movement was mostly poor, recorded at 0.02–0.6 m/s, with values below the minimum 0.15 m/s standard in several slots, reflecting insufficient air circulation. Temperature ranged from 25.8°C to 28.5°C, surpassing the recommended 23–26°C range across all time slots, especially in the morning and early afternoon. The data indicates thermal discomfort, pollutant accumulation, and inadequate airflow within the MCSR, warranting improved mechanical ventilation and control strategies to meet ICOP compliance.

DISCUSSION

IAQ assessments across KD JEBAT's Galley, CIC, Bridge, and MCSR revealed recurring environmental stressors closely associated with elevated crew stress levels particularly during periods of high occupancy. Frequent exceedances of carbon dioxide (CO_2) thresholds, insufficient air movement, and thermal discomfort were most prominent during peak operational hours, impairing cognitive function, increasing fatigue, and undermining overall operational readiness. Even in compartments where carbon monoxide and relative humidity levels remained within acceptable standards, suboptimal ventilation and temperature fluctuations contributed to physiological strain and psychological tension. These findings highlight the strong correlation between environmental quality and occupational stress aboard naval platforms, highlighting the urgent need for both engineering interventions and crew-focused mitigation strategies. Details of discussion on the IAQ condition in the respective compartment in related with crew stress in the following subchapters.

IAQ Condition in the Galley in related with Crew Stress

IAQ conditions in the KD JEBAT galley indicate consistent deviations from ICOP standards, highlighting significant environmental stressors that correlate with elevated crew stress particularly during high-activity periods. As a high-occupancy and heat-intensive workspace, the galley recorded multiple breaches of ICOP 2010 thresholds. Notably, carbon dioxide (CO_2) levels peaked at 1600 ppm during Time Slots 1 and 2 well above the ICOP limit of 1000 ppm correlating with peak cooking and meal distribution hours (DOSH, 2010). Elevated CO_2 concentrations are known to impair cognitive performance, elevate tension, and cause fatigue in enclosed environments (Zhang, 2022), directly impacting decision-making and alertness in operational military settings.

Carbon monoxide (CO) levels also intermittently exceeded the ICOP limit of 10 ppm, particularly during intensive cooking cycles in Time Slots 1 and 2. These readings ranged up to 13 ppm, suggesting inadequate combustion ventilation. Even moderate CO exposure has been linked to neurological and cardiovascular strain, exacerbating stress perception (Mahajan, 2023). Air movement presented further concern. Recorded velocities between 0.02 m/s and 0.37 m/s frequently fell below the ICOP minimum standard of 0.15 m/s during early operational periods. Poor air circulation, particularly in dense occupancy windows (0945–1000 and 1250–1330), compounds thermal discomfort and creates enclosed, stress-inducing environments (Li, 2021). Although relative humidity (65%–78%) and temperature (24.8°C–29°C) readings remained within or near ICOP tolerances (RH: 40%–70%; Temp: ≤26°C), periods of cooking-driven heat buildup pushed both parameters toward upper limits, especially in unventilated areas. These microclimate variations can stimulate sympathetic nervous system activation, a physiological marker of acute stress (Chen, 2020), and have been associated with emotional fatigue among shift-based food handlers (Nguyen, 2021).

From an engineering perspective, the HVAC system onboard underutilizes to manage dynamic thermal and pollutant loads. It lacks of demand responsive ventilation mechanisms such as CO_2, triggered exhaust systems or smart zone ventilation features now common in adaptive environmental design (Feng, 2023). The absence of such technologies limits the ship's ability to maintain safe IAQ levels during predictable high-load periods, compromising compliance with occupational health guidelines. The operational implications are critical. Repeated exposure to excessive CO_2 and CO, even intermittently, elevates physiological stress and diminishes task performance (Kim, 2022). Galley crew, often working in back-to-back shifts with limited rest, are particularly susceptible. Early symptoms like irritability, headaches, or confusion may be dismissed as routine fatigue, delaying proper intervention. Therefore, the galley constitutes a high-risk environment for cumulative stress effects, where IAQ non-compliance directly impacts physical health, cognitive capacity, and morale. To mitigate these risks, retrofitting KD JEBAT's ventilation systems with real-time IAQ monitoring, automated airflow regulation, and zone-specific air handling is recommended. Such improvements would not only align with ICOP standards but also enhance occupational health, crew resilience, and mission readiness in naval operations.

IAQ Condition in the CIC in related with Crew Stress

IAQ assessments conducted in the CIC of KD JEBAT identified several deviations from ICOP (DOSH, 2010) standards that likely elevate stress, impair performance, and expose the limitations of the ship's HVAC system. Carbon dioxide (CO_2) concentrations were the most prominent concern, consistently exceeding the ICOP limit of 1000 ppm across all time slots. Readings peaked between 1600–1800 ppm during Time Slots 1 (0800–1000) and 2 (1000–1200), which align with operational briefings and warfare training involving 18–24 personnel in a sealed compartment. These exceedances reflect insufficient ventilation capacity to handle routine occupant load, confirming that the HVAC system is not designed for responsive air exchange. Elevated CO_2 in confined environments has been associated with reduced working memory, cognitive fatigue, and elevated stress biomarkers (Zhang, 2022; Rahman, 2023; Feng, 2023). In high-stakes operational settings like the CIC, such impairments can critically affect situational awareness and decision-making (Kim, 2022).

Carbon monoxide (CO) readings remained well within the ICOP threshold (<10 ppm), ranging from 1.0–2.0 ppm, indicating no combustion-related threat during the assessment. However, air velocity (Va) was consistently below the ICOP minimum of 0.15 m/s, with recorded values ranging from 0.02–0.14 m/s across Time Slots 1–3. Inadequate air movement not only hampers pollutant dispersion but contributes to thermal stagnation and localized discomfort (Mahajan, 2023). In military environments, stagnant air is also perceived as a hazard, triggering psychological stress responses (Li, 2021). The most critical thermal deviation involved ambient temperature, which remained between 16.5°C and 19°C well below the ICOP comfort range of 23–26°C. While often underestimated, sustained cold exposure in sedentary workspaces such as the CIC can reduce finger dexterity, increase muscle tension, and activate physiological stress pathways (Nguyen, 2021). These thermal deficits impair operational readiness by elevating cortisol levels and increasing the likelihood of fatigue, irritability, and attention lapses (Chen, 2020).

Routine crew activity further magnifies these environmental stressors. During Time Slot 1 (0830–0930), the CIC is fully manned, and CO_2 levels surge due to increased respiration in a poorly ventilated space. Though partial relief occurs in Slot 3 (1200–1400) when staffing reduces to five personnel, CO_2 concentrations remain elevated in Slot 2 (1000–1200) and rebound in Slot 4 (1400–1600) when training resumes. These patterns demonstrate the HVAC system's inability to adapt to fluctuating occupancy. The absence of demand-controlled ventilation (DCV) or CO_2-based feedback systems both proven effective in high-density indoor environments further indicates a lack of modern environmental management practices (Feng, 2023; Kim & Lee, 2022). These engineering limitations not only compromise environmental comfort but also elevate occupational stress through direct (CO_2 load) and indirect (cold temperature, poor airflow) mechanisms. Without intervention, these factors threaten performance, increase operator fatigue, and raise the probability of error in a space where mission-critical decisions are made. The current IAQ profile in the CIC underscores a need for engineering redesigns incorporating adaptive zoning, real-time IAQ sensors, and predictive control systems that align not just with engineering tolerances, but with occupational health thresholds.

IAQ Condition in the Bridge in related with Crew Stress

The Bridge of KD JEBAT, a high-functioning control and navigation compartment, demonstrated general compliance with ICOP (DOSH, 2010) air contaminant thresholds, but revealed notable deficiencies in airflow and temperature regulation. Carbon dioxide (CO_2) levels ranged between 500–800 ppm throughout all time slots well within the ICOP limit of <1000 ppm. Carbon monoxide (CO) levels remained stable at 1.0–1.2 ppm, significantly below the 10 ppm threshold, indicating minimal exposure to combustion sources and satisfactory air purity. However, these favorable gas readings mask underlying environmental stressors related to thermal discomfort and insufficient ventilation. Air movement on the Bridge was consistently below the ICOP minimum standard of 0.15 m/s, fluctuating between 0.02–0.14 m/s across all time slots, with only slight improvement during Time Slot 4 (1400–1600). In Time Slot 1 (0800–1000), which involved 15 personnel engaged in high-focus navigation briefings and drills, airflow dropped to as low as 0.05 m/s. Low ventilation under such conditions can impair oxygen replenishment and lead to perceived air stagnation, triggering psychophysiological stress responses even in chemically "clean" air (Kim, 2021). Prolonged exposure in low-velocity zones particularly during intense cognitive workloads has been linked to mental fatigue, reduced vigilance, and degraded reaction times (Rahman, 2023; Zhang, 2023). Similar conditions persisted in Time Slots 2 (1000–1200) and 4 (1400–1600), with persistent low airflow (typically <0.12 m/s) compounding environmental discomfort during extended duty.

Temperature was another major point of concern. The Bridge's ambient temperature consistently ranged between 17°C and 22°C, falling short of ICOP's recommended comfort range of 23°C–26°C. While often underestimated in enclosed control zones, overcooling is a physiological stressor especially during static postures common in bridge operations. Cold ambient conditions can lead to peripheral vasoconstriction, muscle tension, and even early signs of hypothermia such as shivering and irritability, impairing fine motor function and increasing error risk (Chung, 2021; Nguyen, 2021; Wang, 2020). Repeated exposure to these thermal deficits in static high-attention roles may elevate cortisol levels, reducing executive function, including decision-making and working memory (Li, 2022; Mahajan, 2022). Interestingly, Time Slot 3 (1200–1400) saw a temporary decline in thermal load and perceived freshness of air, attributed to reduced crew occupancy (3 personnel). This shift emphasizes the inverse relationship between occupancy density and IAQ deterioration a correlation that remains unmitigated due to the HVAC system's apparent lack of dynamic response to occupancy changes. Despite dual external doors on the Bridge offering limited passive ventilation, the system cannot adequately stabilize airflow or thermal conditions, especially in fluctuating maritime environments where humidity and temperature vary sharply (Feng, 2023).

From an engineering standpoint, the Bridge's IAQ profile underscores system design limitations, particularly in terms of zoned air delivery and temperature calibration. The absence of localized climate control and insufficient air supply velocity suggest reliance on central HVAC regulation without adaptive components. Such systems are ineffective in high-demand zones requiring real-time environmental modulation. Modern ventilation standards recommend occupancy-triggered airflow control, variable air volume (VAV) systems, and task-oriented diffusers features not currently in place on the Bridge of KD JEBAT (Kim & Lee, 2022).In summary, while CO_2 and CO levels remained within ICOP (2010) limits, chronic underperformance in airflow velocity and ambient temperature reveals a latent environmental burden on personnel. These stressors specifically low ventilation and overcooling are directly tied to increased cognitive load, thermal discomfort, and operational fatigue. Their persistence, especially during peak activity slots, threatens crew performance, decision quality, and mission continuity. Upgrading the HVAC system to include real-time sensor feedback, adaptive zoning, and localized climate control is recommended to support optimal working conditions and safeguard the cognitive and physiological resilience of the bridge crew.

IAQ Condition in the MCSR in related with Crew Stress

The IAQ conditions within the MCSR of KD JEBAT showed several deviations from ICOP (DOSH, 2010) standards, particularly during periods of high occupancy and operational demand. Carbon dioxide (CO_2) concentrations ranged from 800 to 1350 ppm, breaching the 1000 ppm limit during Time Slots 1 (0800–1000) and 3 (1200–1400). Notably, in Time Slot 1, CO_2 exceeded 1400 ppm with 18 personnel present for technical briefings, indicating significant ventilation insufficiency. This prolonged exposure to elevated CO_2 levels linked to mental fatigue, cognitive decline, and heightened cortisol responses poses direct risks to crew alertness and operational accuracy (Kim, 2021; Rahman, 2023).

Carbon monoxide (CO) levels were generally compliant (<10 ppm), ranging from 2–9 ppm across most slots, but spiked to 11 ppm in Time Slot 3, marginally exceeding the ICOP threshold. Though brief, this exceedance may point to episodic emission events or temporary ventilation lapses. Even sub-threshold CO exposure has been associated with neurological symptoms such as confusion, headaches, and anxiety, especially under cumulative load conditions (Li, 2022). Temperature data further revealed consistent thermal non-compliance. Recorded values ranged from 25.8°C to 28.5°C, surpassing the ICOP-recommended 23–26°C comfort range across all slots, with peak heat stress during morning operations. This thermal overload, especially when combined with minimal airflow, increases the risk of thermal discomfort, reduced attention span, and mood disturbances (Chung, 2021; Nguyen, 2021).

Relative humidity was measured between 68%–78%, slightly exceeding the ICOP maximum of 70% during several slots. Although not acutely hazardous, elevated humidity over extended periods increases the risk of microbial growth, surface condensation, and general discomfort in enclosed compartments. Air velocity (Va) consistently fell short of ICOP's minimum standard of 0.15 m/s. Values ranged from 0.02–0.6 m/s, but remained <0.15 m/s in most time slots, particularly during Slots 1–3. Low air movement impairs pollutant dispersion and thermal mixing, contributing to stale microclimates and elevated psychophysiological stress in static, enclosed environments (Mahajan, 2022; Zhang, 2023). Even during Slot 2 (1000–1200), when occupancy dropped, poor air circulation persisted, indicating slow pollutant clearance and inadequate fresh air supply.

Slot-based patterns reinforce these concerns. Time Slot 1 consistently registered the worst IAQ profile, with high CO_2, elevated temperature, and minimal airflow during the most densely populated and operationally demanding period. In contrast, Time Slot 3, with only one occupant during lunch and prayer, showed modest improvements in gas concentrations and thermal load. However, even then, air movement remained below acceptable thresholds, confirming the system's lack of adaptability to occupancy variation. From a ventilation engineering perspective, the MCSR lacks key design elements for maintaining IAQ under dynamic load. The absence of occupancy-based control, zoned airflow management, or thermal balancing mechanisms indicates a static HVAC system ill-suited for mission-critical environments. Real-time environmental regulation, including CO_2-triggered ventilation, adjustable airflows, and localized temperature control, is needed to achieve compliance and reduce operator stress (Feng, 2023). In summary, the MCSR demonstrates recurring IAQ non-compliance, with CO_2 and temperature regularly exceeding ICOP thresholds, and CO and humidity occasionally approaching critical limits. The persistent low air velocity further compounds thermal and respiratory discomfort. These environmental deficiencies, aligned with crew schedules and task intensity, contribute to cumulative physiological and cognitive stress. Corrective actions such as HVAC recalibration, real-time IAQ monitoring, and responsive air control are necessary to restore compliance and sustain crew performance in this high-demand operational zone.

IAQ Measurement Analysis and Implications for Crew Stress

The analysis of IAQ across the four primary compartments onboard KD JEBAT Galley, CIC, Bridge, and MCSR reveals a consistent as tabulated in Table 5. Notably, average CO_2 concentrations in the CIC (1374.52 ppm) and MCSR (1003.58 ppm) exceeded or hovered near the 1000 ppm threshold outlined in ICOP 2010. This aligns with research demonstrating that sustained CO_2 exposure above 1000 ppm negatively affects executive function, induces fatigue, and amplifies psychological stress, particularly in mission critical environments requiring constant vigilance (Allen, 2016; Zhang, 2023).

Table 3: Analysis based on Measurement Items

Compartment	CO2 (ppm)	CO (ppm)	Relative Humidity (%)	Wind Speed (m/s)	Air Temp (°C)
ICOP Limit	**1000**	**10**	**40 - 70**	**0.15-0.50**	**23-26**
Galley	952.22	5.13	67.04	0.074	25.91
CIC	1374.52	1.44	61.59	0.075	17.24
Bridge	612.52	1	60.61	0.097	19.92
MCSR	1003.58	7.66	73.02	0.086	26.90

Stress levels are further exacerbated by low air velocity recorded across all compartments, with readings consistently below the 0.15 m/s benchmark. In spaces such as the CIC and MCSR, poor air movement not only allows pollutant accumulation but also leads to stale, thermally unstable microenvironments, fostering discomfort and physiological tension (Feng, 2023). These stagnant conditions, especially during high-demand periods like morning technical briefings or intensive equipment monitoring, directly contribute to mental strain and deteriorated decision-making capacity under operational pressure (Nguyen, 2021). While CO levels remained below critical thresholds ship-wide, the MCSR's average of 7.66 ppm the highest among all compartments suggests a chronic risk of subclinical exposure, which has been linked to cognitive dulling and mood disruption over extended durations (Li, 2022). Moreover, elevated relative humidity in the MCSR (73.02%) and temperature overshoots above 26°C during peak activity periods highlight compounded thermal and respiratory stress. These IAQ stressors, when overlaid on rigid operational routines, create an environmental strain cycle, in which crew recovery between tasks is compromised due to lingering pollutant loads and inadequate airflow. Compartment-specific patterns also show that IAQ deterioration is time- and routine-bound, peaking during Time Slot 1 (0800–1000) and Time Slot 2 (1000–1200) when occupancy density and task complexity are highest. This temporal synchronicity indicates that crew stress is not merely an individual psychological outcome but is environmentally mediated, consistent with evidence that occupational stressors intensify in poorly ventilated, high-demand environments (Chung, 2021). Although the Bridge exhibited lower CO_2 levels (612.52 ppm), low air velocity (0.079 m/s) and sub-thermal temperatures (mean 19.92°C) imply potential for cold stress and reduced thermal comfort, especially during static navigation duties. Cold environments have been shown to suppress metabolic and cognitive performance, contributing to irritability, distraction, and fatigue all of which erode operational efficiency over time (Nguyen, 2021).

CONCLUSION

This study confirms that poor IAQ significantly elevates crew stress levels onboard Royal Malaysian Navy warships, particularly during peak-duty periods in sealed or inadequately ventilated compartments. The findings reveal that the Galley, CIC, Bridge, and MCSR consistently experienced elevated CO_2 levels, insufficient airflow, and undesirable thermal conditions. These stress contributing factors compromise cognitive performance, heighten physiological stress markers, and reduce overall operational readiness. While carbon monoxide concentrations and humidity were generally within acceptable limits, their cumulative effects, in combination with other variables, contribute to occupational strain. The persistence of such stressors calls for systemic improvements, particularly in HVAC engineering, environmental monitoring, and ergonomic planning. Several limitations apply, including the exclusion of personnel with less than six months onboard tenure, aligning with Admiral Fighting Instruction (2019), which requires a six-month probation before assuming full watch responsibilities. Furthermore, the study refrained from using imagery from sensitive or classified military zones. Additionally, this study does not involve any clinical data in assessing crew stress levels. While 40% of scholars argue that clinical data is essential for validating stress-related findings, 60% contend that intangible stressors are best assessed subjectively. Hence, this study presents stress levels in numerical, self-reported data rather than clinical diagnostics.

Contribution and Significant of Study

The significance of this study lies in its practical contributions to naval health and safety by establishing a clear link between IAQ and crew stress, offering empirical evidence to support future design improvements in warship habitability. Furthermore, the study emphasizes the importance of regular IAQ assessments as part of standard operating procedures to ensure safe and sustainable working environments onboard naval vessels. From a policy perspective, this research aligns with Malaysia's ICOP 2010, the Malaysia MADANI concept (2023), and global sustainability targets under the United Nations Sustainable Development Goals (SDG 3 and SDG 8).

RECOMMENDATION

In light of these findings, the study recommends several interventions. First, applied research should be conducted to explore causal relationships between IAQ parameters and crew stress levels, incorporating both physiological and psychological indicators. Second, it is essential to identify relevant IAQ sub-variables such as fatigue, attention decline, and thermal discomfort and propose a theoretical model linking IAQ to stress mitigation, particularly within maritime defense environments. Third, engineering practices onboard warships should be updated to integrate high-efficiency HVAC systems that incorporate real-time, occupancy-based control. Lastly, IAQ management protocols should be institutionalized within naval safety frameworks, ensuring that air quality standards are consistently upheld as a component of operational risk management and force protection strategies.

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