ADVANCING DEFENCE CAPABILITY THROUGH TECHNOLOGY, HUMAN FACTORS AND OPERATIONAL INNOVATION

FRONTIER

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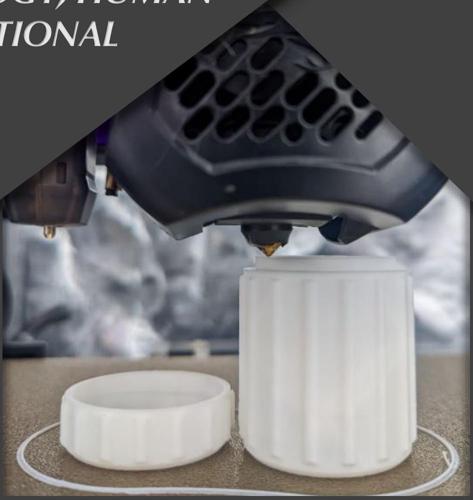

DEFENCE SCIENCE AND TECHNOLOGY GROUP
MINISTRY OF DEFENCE, BRUNEI DARUSSALAM

FRONTIER

VOLUME 7

FRONTIER
Vol. 7: *Advancing Defence Capability through Technology, Human Factors and Operational Innovation*

Ministry of Defence Brunei Darussalam

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The Frontier Team

Interested authors may e-mail their queries to the Defence Science and Technology Secretariat at def.technology@mindef.gov.bn

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About FRONTIER

FRONTIER is a Defence Science and Technology (DS&T) journal formatted under the guidance of the Defence Science and Technology Group (DSTG), for the periodic publication of a curated set of articles, reports and technical papers written by members of the Ministry of Defence (MINDEF) and the Royal Brunei Armed Forces (RBAF), as well as the institutions of higher learning in Brunei Darussalam.

Through publication and hence sharing of DS&T content, FRONTIER aspires to be a platform that creates awareness, generates discussion an inculcates innovation among members of the DS&T community.

In alignment with the ongoing digitisation effort spearheaded by DSTG, FRONTIER will be made available primarily as softcopy via the MINDEF official website. Limited hard copies of FRONTIER will also be distributed to MINDEF and RBAF leaderships and made available in MINDEF and RBAF libraries.

FOREWORD

The Defence Science and Technology Group (DSTG) is pleased to present the seventh volume of *FRONTIER*, themed *"Advancing Defence Capability through Technology, Human Factors and Operational Innovation."*

This edition brings together a collection of articles reflecting ongoing efforts within the Royal Brunei Armed Forces (RBAF) and the wider Defence Science and Technology community to strengthen operational effectiveness, adaptability, and resilience. The contributions span key areas including corrosion detection in tropical environments, advancements in military clothing and personal protective equipment, human factors and ergonomics in air operations, safety culture within the Royal Brunei Air Force (RBAirF), additive manufacturing technologies, and the application of virtual reality in training.

The first article, *"A General Overview of Corrosion Detection Methods and Their Applicability in Tropical Defence Operations,"* examines the challenges posed by Brunei Darussalam's climate and evaluates detection approaches to support proactive maintenance and improve asset readiness. *"Innovative Military Clothing and Gear for the Royal Brunei Armed Forces"* explores opportunities to enhance heat resilience, safety, and operational performance through improved design and emerging technologies.

"Human Factors and Ergonomics in RBAirF" highlights the influence of environmental and physiological stressors on aircrew performance, reinforcing the importance of integrating human considerations into capability development. This is complemented by *"Strengthening Safety Culture in the Royal Brunei Air Force: From Compliance to Commitment,"* which reflects the shift towards a more proactive and values-driven safety culture.

In addition, *"Overview of Additive Manufacturing Technologies for Military Industries"* provides insight into emerging technologies that offer greater flexibility in support functions, while *"Virtual Reality (VR) Winch Training"* demonstrates the potential of immersive technologies to enhance training effectiveness and operational readiness.

Collectively, the articles in this volume reflect continued efforts to advance defence capability through the integration of technology, human factors, and operational innovation. They contribute valuable perspectives to support informed decision-making and reinforce the importance of sustained investment in Defence Science and Technology to ensure the RBAF's continued readiness and resilience.

Hasrinah binti Matyassin
Editor-in-Chief

About the Author

- ***Dr Nurhazwana binti Haji Jumat***

  She is a Research Officer at the Centre of Science and Technology Research and Development (CSTRAD), where she specialises in Tropical Environment Research, investigating the effects of tropical climatic conditions on materials, systems, and human performance. She holds a PhD in Geosciences from Universiti Brunei Darussalam. Dr Nurhazwana has contributed to several research projects in Defence Science and Technology, with a particular interest in applying scientific insights to support sustainable and resilient operational systems in tropical environments.

A GENERAL OVERVIEW OF CORROSION DETECTION METHODS AND THEIR APPLICABILITY IN TROPICAL DEFENCE OPERATIONS

Dr Nurhazwana binti Haji Jumat
Centre of Science and Technology Research and Development (CSTRAD)
Ministry of Defence

ABSTRACT

Corrosion poses a significant threat to structural integrity, operational readiness, and maintenance efficiency, particularly in environments characterised by high humidity, salt exposure, and biological activity. Brunei Darussalam's tropical climate amplifies these risks, underscoring the need for early-stage corrosion detection strategies tailored to the local environment. In this paper, a spectrum of corrosion detection techniques such as visual inspection, non-destructive testing (NDT), corrosion coupons, X-ray fluorescence (XRF), scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), and electrochemical methods is evaluated based on detection capability, environmental resilience, and operational feasibility. This paper further highlights the corrosion risks facing the Royal Brunei Armed Forces (RBAF) and the existing gaps in current detection strategies, such as limited data, underutilisation of advanced tools, and shortage of corrosion science expertise. The findings from this paper advocate for a more integrated, climate-specific detection framework to support proactive maintenance, improve asset performance, and enhance long-term defence readiness.

Keywords:
Corrosion Detection, Defence, Tropical Environment, NDT, XRF, SEM-EDS

1.0 INTRODUCTION

Corrosion is generally defined as the gradual degradation of materials as a result of chemical or electrochemical process with the surrounding environment. It is an inherently detrimental process, often resulting in the progressive loss of material properties, structural integrity and structural performance. The Association for Materials Protection and Performance (AMPP) defines corrosion as the deterioration of a material, often a metal, caused by a reaction with its environment [**1**]. The U.S. Department of Defense similarly characterises corrosion as the deterioration of the properties of a material due to a reaction of the material with its chemical environment [**2**].

Corrosion remains a persistent and costly challenge across various industrial sectors globally with profound implications. It compromises the functionality and safety of engineering systems, elevates maintenance costs and poses significant environmental hazards. Structurally, it jeopardises the integrity of critical infrastructure such as pipelines, aircraft, marine vessels, and military assets. The global economic strains resulting from corrosion has been estimated to exceed USD 2.5 trillion annually, which accounted for approximately 3.4% of global GDP as of 2013 [3]. In safety-critical industries such as transportation, defence, and energy, undetected or poorly-managed corrosion can result in catastrophic consequences including infrastructure failure, environmental contamination, and loss of life. These realities underscore the need for reliable and proactive corrosion detection and monitoring systems to ensure operational reliability, cost-efficiency, and asset longevity.

For Brunei Darussalam, corrosion risks are exacerbated by its tropical equatorial climate characterised by hot, humid, and saline environmental conditions, which features average temperatures between 26°C and 32°C and relative humidity between 80% and 90% all year round, with an annual rainfall surpassing 3,000 mm [4]. These persistent environmental stressors create ideal conditions for the onset and acceleration of corrosion processes. In coastal and low-lying regions, the risk is further intensified by exposure to salt-laden winds, tidal fluctuations, and biological activity. Such conditions facilitate aggressive corrosion mechanisms, including pitting, crevice corrosion, and microbiologically influenced corrosion (MIC), which can develop more rapidly and be harder to detect than general corrosion. For defence infrastructure and military platforms, these environmental challenges pose significant risks to asset readiness, longevity, and safety. In such an aggressive climate, the absence of seasonal reprieve means military assets remain under continuous exposure.

While corrosion monitoring involves long-term tracking of environmental exposure and material degradation over time, corrosion detection is primarily concerned with the timely identification, localisation, and characterisation of damage once it begins to manifest. In military applications, where equipment reliability, mission continuity, and personnel safety are paramount, effective corrosion detection forms a critical first line of defence. Unlike preventive strategies that rely on coatings, cathodic protection, or environmental control, detection techniques serve to uncover active or latent corrosion that may not yet be visible but could soon compromise structural integrity or system performance. Given these risks, there is a pressing need for corrosion detection methods that align with Brunei Darussalam's specific climate and operational demands. This article aims to explore a range of corrosion detection methods with an assessment on their effectiveness and feasibility for deployment in tropical, marine-influenced environments which are prevalent Brunei Darussalam.

2.0 CORROSION MECHANISMS IN TROPICAL ENVIRONMENTS

Corrosion is fundamentally driven by the thermodynamic tendency of metals to revert to their more stable states through interaction with the environment. In metallic systems, the formation corrosion cell requires four essential components: an anodic site, a cathodic site, an ionic path, and an electronic path [5].

The process typically initiates through the differentiation of anodic and cathodic regions on a metal surface. At the anode, metal atoms lose electrons through oxidation reactions, and at the cathode, these electrons are consumed by reduction reactions involving environmental elements, such as oxygen or hydrogen ions cathode [6,7]. A classic example is the rusting of iron in the presence of oxygen and moisture, which typically begins with (i) the anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^-$ and (ii) the cathodic reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (for acidic environments) or $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (for neutral to alkaline conditions) [8]. These reactions lead to the formation of iron (III) hydroxide: $4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3$. This compound is unstable and gradually converts into hydrated iron oxide, also known as rust: $Fe(OH)_3 \rightarrow Fe_2O_3{\cdot}xH_2O$.

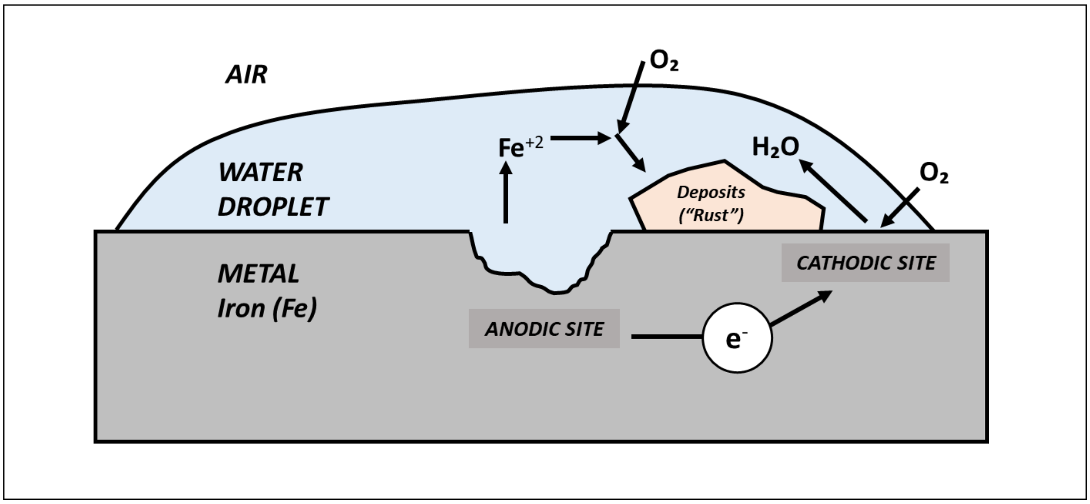

Figure 1. Simplified corrosion mechanism (rusting) for iron.

Corrosion involves two simultaneous currents: (i) an ionic current through the electrolyte, driven by ion movement, and (ii) an electronic current through the metal, driven by electron flow from anode to cathode. Moisture containing dissolved salts serves as the electrolyte and is vital to sustaining this process.

The rate and nature of corrosion are strongly influenced by environmental variables, including temperature, humidity, pH, oxygen availability, and the presence of aggressive ions like chlorides [5,8]. In Brunei Darussalam's tropical environment, these variables are typically extreme and continuous. High humidity facilitates the continuous formation of an electrolyte film on exposed metal surfaces, while elevated temperatures enhance reaction kinetics and diffusion rates [9]. Additionally, frequent wet-dry cycles in equatorial climate further exacerbate corrosion by accumulating surface salts and introducing fluctuating oxygen levels, which in turn promote differential aeration and localised corrosion attack [10].

Coastal infrastructure and offshore installations are especially vulnerable to constant exposure to salt-laden winds, marine aerosols, and tidal fluctuations, all of which drive chloride-induced corrosion. In addition, Brunei Darussalam's biologically rich and low-energy aquatic environments, such as mangrove zones, riverbanks and estuaries, support the formation of biofilms and microbial colonies, thus elevating the risk of microbiologically-induced corrosion. Given these conditions, several corrosion mechanisms are particularly relevant across Brunei Darussalam's infrastructure and operational assets, which are described below.

Uniform corrosion. Uniform corrosion is the most straightforward form, and is characterised by the uniform or even loss of material across a metal surface. It typically occurs on uncoated or inadequately protected structural steels, particularly when exposed to humid or wet conditions over prolonged periods [7].

Pitting corrosion. Pitting corrosion is a localised and highly aggressive form of corrosion, and is often initiated by chloride ions that penetrate and destabilise protective films on metals such as stainless steels and aluminium alloys. This results in small but deep pits which are difficult to detect and can lead to sudden failure [8].

Crevice corrosion. Crevice corrosion develops in confined or shielded areas, where stagnant electrolytes are trapped. Examples include beneath gaskets, washers, fasteners, or overlapping metal joints. The localised depletion of oxygen within the crevice creates differential aeration cells which promote acidification and metal dissolution [6].

Galvanic corrosion. Galvanic corrosion occurs when two dissimilar metals are electrically connected via a conductive medium, such as seawater. The more anodic metal corrodes preferentially, while the more noble metal is protected. This is a common issue in mixed-metal assemblies on military platforms and coastal installations [11].

Microbiologically influenced corrosion (MIC). MIC is a multifaceted form of corrosion which arises as a result of microbial agents, specifically sulphate-reducing bacteria (SRB), iron-oxidising bacteria, and fungi. These organisms produce corrosive metabolic by-products such as hydrogen sulphide or organic acids, effectively altering the local electrochemical environment. MIC is frequently observed in water storage tanks, pipelines, and other bioactive environments [12].

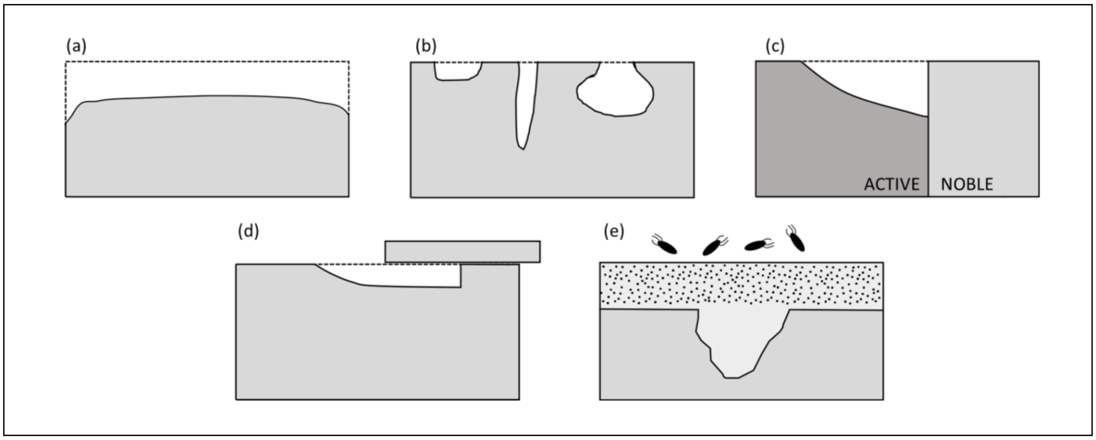

Figure 2. Schematic diagrams of the various corrosion types relevant in tropical environments which include: (a) Uniform Corrosion, (b) Pitting Corrosion, (c) Galvanic Corrosion, (d) Crevice Corrosion, and (e) Microbiologically-influenced Corrosion (MIC).

A summary of the aforementioned corrosion mechanisms is presented in **Table 1**. A thorough understanding of these mechanisms is essential for informed decisions regarding material selection, protective strategies, and corrosion detection technologies suitable for Brunei Darussalam's tropical landscape.

Table 1. Summary of key characteristics of corrosion mechanisms prevalent in tropical environment settings.

Corrosion type	Description	Typical locations	Damage risks	Key drivers
Uniform corrosion	Even material loss across a metal surface	Exposed steel structures in humid environments	Gradual weakening of metal structure over time	Moisture and oxygen exposure over time
Pitting corrosion	Localised, deep pits in specific spots	Coastal structures, stainless steel / aluminium components	Difficult-to-detect damage that can cause sudden failure	Chloride ions breaking down protective surface film
Crevice corrosion	Occurs in tight, shielded spaces where water is trapped	Bolted joints, gaskets, washers, overlaps	Accelerated local attack that weakens joints or seams	Stagnant electrolytes and oxygen depletion in tight spaces
Galvanic corrosion	Occurs when dissimilar metals are electrically connected in a conductive medium	Mixed-metal assemblies	Accelerated corrosion of anodic metal	Contact between dissimilar metals in conductive environment
MIC	Caused by microbial activity (e.g., SRB, iron-oxidising bacteria)	Water tanks, pipelines, estuaries, bioactive zones	Rapid and unpredictable damage in damp areas due to microbes	Microbial colonies producing corrosive by-products

3.0 CORROSION DETECTION TECHNIQUES

Effective corrosion monitoring is crucial for mitigating material degradation and preserving the structural integrity of critical assets. A wide array of detection and evaluation techniques has been employed across various industries to support the identification, quantification and monitoring of corrosion. These methods vary widely in terms of detection sensitivity, equipment requirements, cost, and adaptability to environmental conditions. As such, their suitability and application are strongly dependent on the specific operational context and exposure environments. **Table 2** presents a comparative summary of the key characteristics of the corrosion detection techniques covered in this paper with emphasis on their application in Brunei Darussalam's environment.

Visual Inspection

Visual inspection is the most fundamental and commonly applied technique for detecting corrosion. It involves the direct observation of surfaces for visible signs of degradation such as discoloration, rust formation, blistering, flaking, pitting or cracking. This technique is often conducted with the naked eye or aided by basic tools such as magnifying lenses, flashlights, inspection mirrors, or more advanced equipment like borescopes, or remote visual inspection (RVI) [13].

A primary advantage of the visual inspection technique is that it is non-destructive, cost-effective and easy to implement in both routine maintenance and initial condition assessments. This method is typically employed as a first-line approach in corrosion inspection programs before deploying more advanced diagnostic tools.

Nonetheless, visual inspection also carries significant limitations. This technique is inherently subjective and dependent on the inspector's experience and skills, lighting conditions, and access to the surface. It is largely limited to surface-level corrosion and may fail to detect early-stage, subsurface, or localised corrosion types (e.g. pitting, crevice corrosion and MIC) particularly under insulation, paint coatings or marine growth [14]. In tropical climates, rapid progression of corrosion under coatings or in high-moisture environments means that visual signs may appear only after significant damage has already occurred [15].

To improve reliability, visual inspections are often conducted using standardised grading systems, such as ISO 4628 for coating degradation, ASTM D610 for rust evaluation, or NACE SP0178 for weld and structural inspection criteria [16,17,18]. These standards provide consistent assessment frameworks that help reduce subjectivity and ensure comparable documentation across inspection cycles. Visual evaluations are typically supported by photographic documentation and periodic benchmarking against baseline conditions. Nevertheless, in high-risk environments such as in defence systems or offshore platforms, visual inspection should be supplemented with other non-destructive techniques (NDT), including ultrasonic thickness measurements to detect material loss, dye penetrant testing to detect surface crack, or corrosion monitoring sensors to track real-time corrosion activity [19].

Figure 3. Application of industrial borescopes in various maintenance and inspection scenarios. The handheld devices enable real-time visual inspection of internal structures to detect corrosion, wear, or blockage without disassembly. Image source: Shenzhen Yateks Co. Ltd.

Non-Destructive Testing (NDT)

NDT encompasses a suite of diagnostic techniques used for the detection, characterisation and monitoring of corrosion-related defects without causing damage to the material or structure being tested. Compared to visual inspection, NDT techniques offer greater sensitivity and depth resolution, and possess the ability to identify subsurface flaws, material thinning, and fatigue cracks [20]. These capabilities make NDT especially valuable for inspecting critical assets, where early detection is essential for avoiding catastrophic failures. Common NDT methods are described below.

Ultrasonic testing (UT). UT involves the use of high-frequency sound waves to measure material thickness and to detect internal defects such as corrosion pits and material thinning.

Radiographic testing (RT). RT involves the use of X-rays or gamma rays to create images of internal structures, making it effective for identifying subsurface defects and corrosion in welds and pipe systems.

Eddy current testing (ECT). ECT uses electromagnetic induction to detect surface and near-surface flaws in conductive materials, especially useful for non-ferrous alloys.

Magnetic particle inspection (MPI). MPI involves the application of magnetic fields and iron particles to ferromagnetic materials to highlight surface cracks and stress-induced corrosion features.

NDT methods are constrained by several operational requirements, including the requirement for skilled personnel, properly calibrated instruments, and controlled environmental conditions, in addition to adequately prepared surfaces. In tropical environments with high humidity, rainfall, and temperature fluctuations, maintaining optimal testing conditions during on-site inspections can be logistically demanding, especially in remote or offshore applications [21]. Despite these constraints, NDT remains an essential element of corrosion monitoring strategies. Continued investment in portable, automated, and weather-resilient NDT technologies is recommended for improving effectiveness in tropical deployments.

Figure 4. Technician conducting corrosion detection using phased array ultrasonic testing (PAUT). The setup demonstrates real-time imaging for precise flaw detection and thickness measurement. Source: Evident Scientific.

Corrosion Coupons and Gravimetric Measurement

Corrosion coupons are standardised metal specimens used to assess corrosion behaviour under actual service conditions. These coupons are installed in the operational environment to simulate actual exposure conditions for a defined period, after which the coupons are retrieved, cleaned following standardised procedures and then weighed to calculate mass loss and corrosion rate [22].

This method is particularly valued for its simplicity, cost-effectiveness, and ability to reflect real-world conditions, including the effects of local water chemistry, temperature, biofouling, and flow rate [23]. In tropical climates, corrosion coupons are well-suited for long-term environmental exposure studies, especially in coastal, riverine, and offshore installations [24].

Despite their practicality, corrosion coupons are limited by their inability to perform real-time monitoring, which prohibits applications requiring immediate feedback. Moreover, they typically capture average corrosion rates and may fail to detect localised forms of attack, unless combined with complementary techniques like scanning electron microscopy (SEM) or microbiological analysis [7].

To enhance diagnostic accuracy, corrosion coupons are frequently used alongside electrochemical sensors, biofilm samplers, or chemical analysis of surface deposits, to provide a more comprehensive evaluation of corrosion dynamics in complex or biologically active environments.

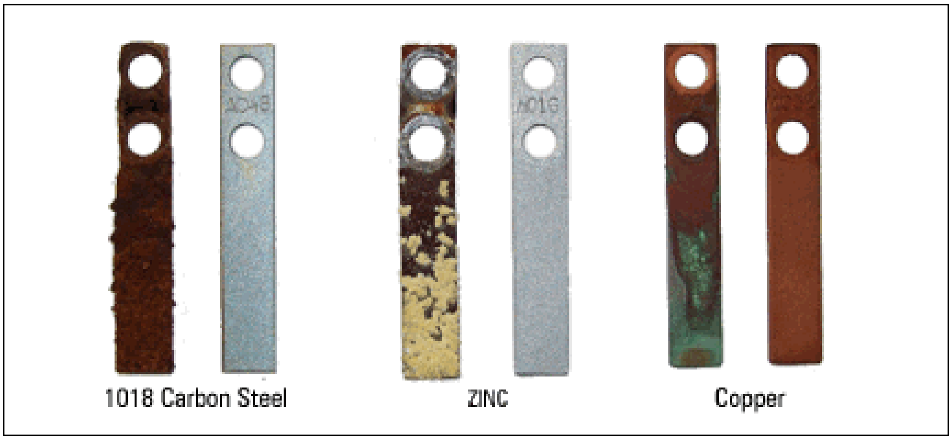

Figure 5. Examples of corrosion coupons made of carbon steel, zinc, and copper before and after exposure. Image source: Caproco Corrosion Prevention Ltd.

X-Ray Fluorescence (XRF)

XRF is a non-destructive spectroscopic technique used to determine the elemental composition of materials by measuring the characteristic secondary (or fluorescent) X-rays emitted from a sample when it is excited by a primary X-ray source. XRF is particularly effective for identifying corrosion products, alloy constituents, surface contaminants, and coating degradation, making it a valuable tool for both material verification and failure analysis [25].

The advent of modern handheld XRF analysers has expanded its applications in on-site inspections across industries. These instruments are capable of rapid and real-time results without damaging the surface, and this quality makes them ideal for spot checks and preliminary diagnostics in operational environments [26].

Despite the aforementioned advantages, XRF performance is subject to several operational variables. Surface conditions (e.g., roughness, moisture, or corrosion products) can attenuate signal quality and affect measurement accuracy. Additionally, reliable results depend on calibration routines and matrix corrections which are essential when measuring thin layers or non-homogeneous corrosion scales. In tropical climates, high humidity and airborne salt particles may complicate surface preparation and consistency, requiring thorough cleaning and repeat measurements to ensure representative readings [27].

Although XRF does not provide depth profiling or identify microstructural defects, it remains a highly effective complementary tool in corrosion monitoring programs. When integrated with visual inspection, microscopy, or electrochemical analysis, it enhances the diagnostic accuracy and comprehensiveness of corrosion assessments.

El	%	+/- 3σ	9 Cr+V
Fe	89.35	0.19	87.60 90.61
Cr	8.06	0.15	8.00 9.50
Mo	0.975	0.025	0.85 1.05
Mn	0.48	0.11	0.30 0.60
Si	0.35	Nom.	0.2-0.5
Ni	0.280	0.059	0.00 0.40

Figure 6. On-site elemental analysis using a handheld XRF analyser to verify pipe alloy composition and identify corrosion risks. Image source: Olympus Corporation.

Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS)

SEM combined with EDS is a powerful analytical technique used for detailed surface analysis and elemental characterisation in corrosion studies. SEM is capable of producing high-resolution imaging of corrosion morphology on the surface of a metal of interest (e.g. surface roughness, crack propagation, or pit geometry) at magnifications exceeding 100,000×. EDS complements this by providing elemental composition data at specific points on the surface, making it highly effective for identifying corrosion products and detecting contaminant species [28].

In tropical settings, SEM-EDS is particularly beneficial in the post-exposure evaluation of corrosion coupons or failure analysis of components upon exposure to humid, saline, or bioactive environments [29]. It provides insights that visual inspection may overlook, such as subsurface pit evolution, microstructural separation, or localised deposits formed in stagnant or microbially active zones.

Despite its analytical advantages, SEM-EDS is inherently a laboratory-based technique and requires vacuum conditions and electrically conductive coatings, as well as skilled personnel. It is not suitable for field deployment, and its relatively high operational costs and preparation requirements often limit its use to forensic-level investigations or research-focused corrosion evaluations [30].

Nevertheless, when integrated into a broader corrosion monitoring framework, SEM-EDS remains an indispensable tool in providing the microstructural evidence needed to validate field observations. Through SEM-EDS, end users are able to enhance understanding of corrosion mechanisms, and support informed decisions in material selection, protection strategies, and overall maintenance planning.

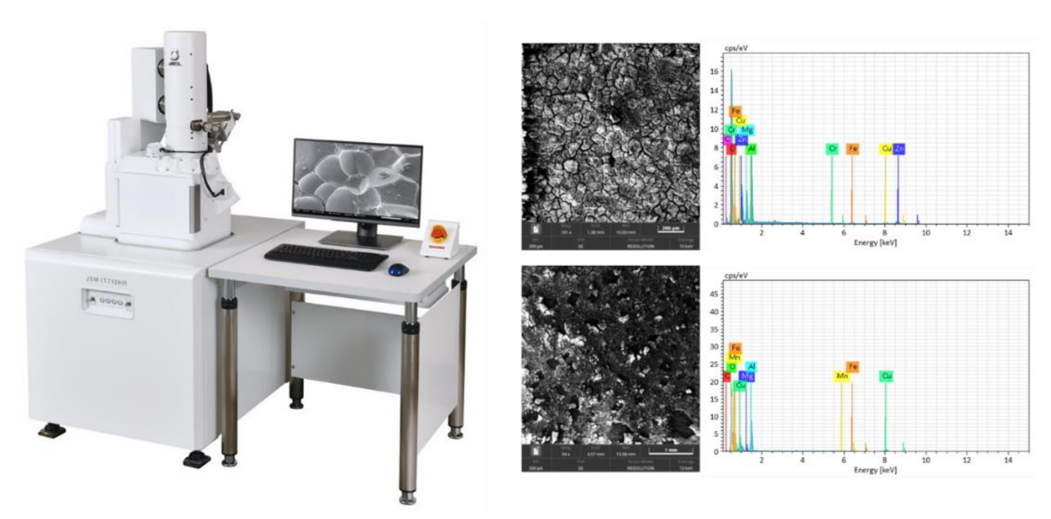

Figure 7. Scanning electron microscope (SEM) for advanced material characterization and microstructural analysis. Image adapted from JEOL USA, Inc.

Electrochemical Techniques

Electrochemical methods like Linear Polarisation Resistance (LPR) and Electrochemical Impedance Spectroscopy (EIS) are commonly used to monitor corrosion, especially in wet or humid environments. These techniques can detect corrosion activity early and provide real-time data about the cause and rate of corrosion of a material of interest [8].

LPR applies a small direct current (DC) voltage sweep near the corrosion potential and measures the resulting current to calculate the polarisation resistance of the studied metal. This resistance is inversely proportional to the corrosion rate, making LPR a fast and effective method for quantifying uniform corrosion in real time [6]. Its simplicity and speed make it well-suited for field applications, though it is less sensitive to early-stage or localised corrosion phenomenon.

EIS works by applying a small alternating current (AC) voltage across a metal surface over a range of frequencies, generating a complex impedance spectrum that provides insights into multiple corrosion-related processes. It is particularly valuable for assessing coating degradation, detecting early signs of corrosion, and evaluating subsurface or microbially influenced corrosion (MIC) [31].

High humidity, heat, and changing electrolytic conditions in tropical environments can make it difficult to get reliable measurements using electrochemical techniques. The equipment also requires stable reference electrodes, clean electrical contacts, and periodic recalibration, which can prove to be logistically challenging to maintain in remote or marine locations [32].

In spite of these limitations, LPR and EIS are important tools for monitoring corrosion. When combined with automated data loggers or remote sensors, their ability to detect corrosion at an early stage makes them valuable for predictive maintenance and asset management strategies.

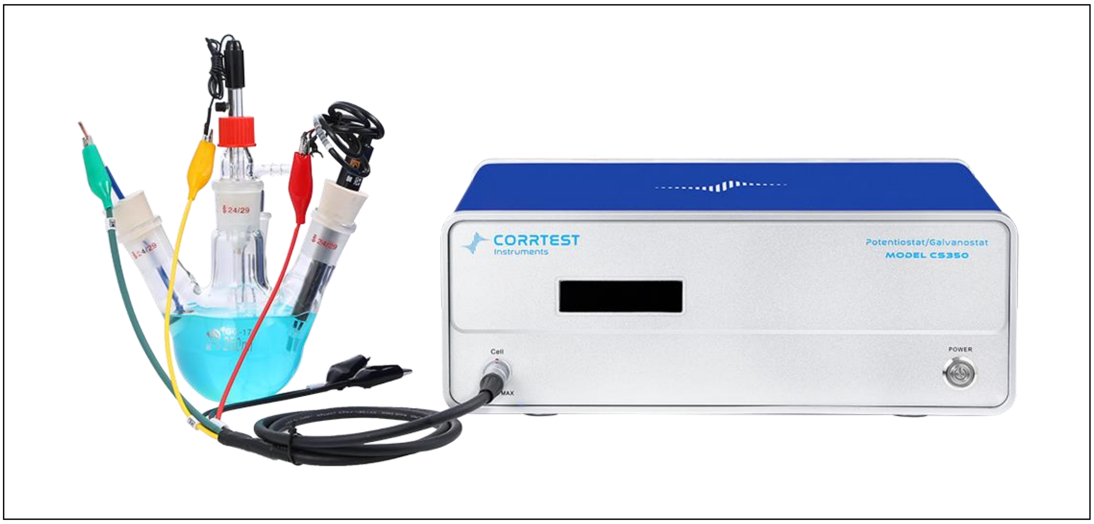

Figure 8. A potentiostat / galvanostat system connected to a three-electrode corrosion test cell for LPR and EIS measurements. The setup includes a working electrode (metal sample), reference electrode, and counter electrode immersed in electrolyte solution. Image source: Corrtest Intruments.

Table 2. Summary of key characteristics of corrosion detection methods and adaptability in tropical settings.

Technique	Description	Strengths	Limitations	In-situ applicability	Suitability in Brunei
Visual Inspection	Basic surface-level inspection for visible signs of corrosion using eyes or tools	Simple, low-cost, non-invasive; easy first-line method	Surface-only; subjective; dependent on visibility and access	Yes; easily performed on-site	Effective for routine checks, but may miss early-stage corrosion due to fast tropical progression

NDT (UT, RT, ECT)	Detection of subsurface flaws without damaging the material	High sensitivity to subsurface flaws; critical asset suitability	Needs skilled operators, calibrated tools, and controlled settings	Conditional; can be used on-site with preparation and trained personnel	Useful for structural and offshore inspections; deployment can be challenged by humidity and access
Corrosion Coupons	Exposure of metal samples in real environments for corrosion assessment through mass loss	Represents real environmental exposure; long-term monitoring	No real-time data; limited localised corrosion insight	Yes; widely used for long-term exposure studies	Well-suited for riverine, coastal, and marine monitoring; reliable long-term trends
XRF	Identification of elemental composition	Rapid field analysis of elemental composition and coatings	Affected by surface conditions; lacks depth resolution	Yes; portable analysers suitable for field diagnostics	Field-portable; good for fast screening, but needs surface prep in humid / salty environments
SEM-EDS	High-resolution imaging and elemental microanalysis	High-resolution analysis of morphology and corrosion products	Lab-based; costly; requires vacuum and preparation	No; laboratory-based only	Ideal for post-exposure coupon analysis in harsh tropical conditions
Electrochemical techniques (LPR, EIS)	Electrochemical measurements of corrosion rate	Real-time detection of corrosion rates and protective coating performance	Sensitive to setup and environmental stability; complex data Interpretation	Conditional; increasingly adaptable with probes / sensors	Crucial for early-stage and kinetic insights; humidity and bioactivity complicate in-situ use

Each corrosion detection technique presents unique advantages and limitations in terms of sensitivity, accessibility, cost, and applicability under local environmental conditions. Visual inspection remains widely used for its simplicity and low cost, while NDT enables the detection of subsurface in critical components. Corrosion coupons provide valuable long-term exposure data, XRF allows for rapid elemental analysis at the surface, and SEM-EDS facilitates detailed failure analysis at microscopic level Electrochemical methods allow for real-time corrosion monitoring but require controlled conditions and regular maintenance. In Brunei Darussalam's hostile tropical climate, where high humidity, salinity, and biological activity accelerate corrosion, a combined approach integrating multiple techniques based on asset type and exposure conditions offers the most effective foundation for early corrosion detection and informed maintenance planning.

4.0 CORROSION DETECTION IN DEFENCE

Corrosion remains a persistent threat to the operational readiness, safety, and cost-effectiveness of military assets. The financial burden due to corrosion is substantial, with recent estimates published by the U.S. Department of Defense of annual costs exceeding USD 20 billion, a figure which represents nearly 20% of their maintenance budget [33]. In the case of Brunei Darussalam, harsh local environmental conditions create a high-risk setting for material degradation across a wide range of military platforms and assets. As such, effective corrosion detection imperative in preventing mission-critical failures and extending asset lifespan. Military platforms vary in their exposure risks and structural vulnerabilities, hence requiring domain-specific detection strategies that blend different types of techniques. Key platform categories are outlined below.

Naval vessels and amphibious craft. Naval platforms are exposed to a continuous cycle of saltwater contact, tidal fluctuations, and marine aerosols. These conditions promote corrosion processes such as pitting, crevice corrosion, and MIC, particularly in confined areas such as ballast tanks, bilges, and sea water cooling systems [24]. The high salt content in seawater breaks down protective layers on metal alloys, while warm and still water in compartments encourages bacteria growth that speeds up localised corrosion. In these settings, visual inspection remains the most accessible method for identifying paint degradation, surface rusting, or weld defects, aided by remote visual tools like borescopes for confined spaces [34]. To stimulate real-world exposure, corrosion coupons are commonly deployed in ballast tanks and seawater systems, with mass loss used to estimate corrosion rates over time [35]. Electrochemical techniques such as LPR are valuable for tracking real-time corrosion kinetics in submerged components, including hull interiors or pipework [36]. In failure investigations, SEM-EDS is essential for characterising pitting morphology and identifying microbial or chloride-induced corrosion products [30].

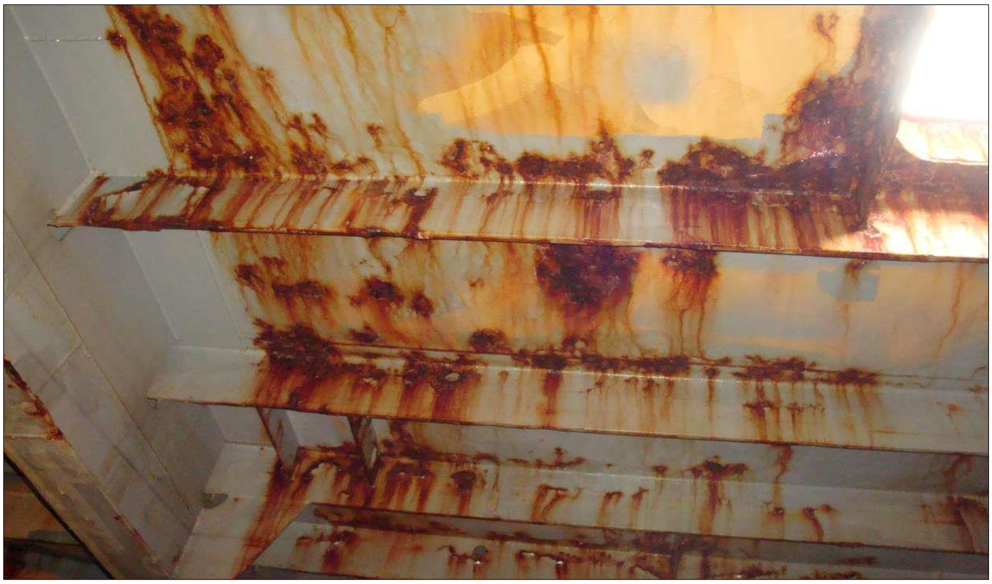

Figure 9. Severe internal corrosion observed in a ballast tank of a vessel. The image highlights extensive rust formation, coating failure, and pitting corrosion. Image source: Chemco International.

Armoured and wheeled vehicles. Vehicles deployed in jungle terrain or coastal areas accumulate mud and moisture in undercarriages and suspension systems. Combined with temperature fluctuations and microbial activity, these factors contribute to under-deposit corrosion and accelerated breakdown of coatings, especially where water is retained in seams or fastener joints [14], which consequently exposes the bare metal to corrosive environments. Visual inspection remains a principal tool, although its limitations in detecting early-stage or subsurface damage are well documented [37]. NDT methods such as UT and EC testings are widely applied for detecting weld defects, hidden pitting, and material thinning, especially in suspension and chassis components [20]. Portable XRF is increasingly used in depot settings for identifying material changes, surface contamination, or corrosion scale composition, especially on aluminium or high-strength steel components [28]. For advanced failure analysis, SEM-EDS offers high-resolution imaging of corrosion propagation beneath coatings or around fasteners [28].

Military aircraft. Military aircraft are typically constructed using a combination of dissimilar metals such as aluminium, titanium, and stainless steel, which are susceptible to galvanic corrosion when exposed to electrolytes like residual salts and condensation. Frequent wet-dry cycles contribute to the build-up of salts on aircraft surfaces and under fasteners, which deteriorate protective coatings and accelerate corrosion at joints and interfaces [38]. These effects are further aggravated by inadequate drainage and sealing, especially in grounded or parked aircraft, where moisture is likely to accumulate. Routine visual inspections are typically conducted alongside scheduled maintenance and increasingly supported by drones or endoscopic tools for improved accessibility [39]. EC testing is the preferred NDT technique for aircraft corrosion detection due to its suitability for non-ferrous alloys and fastener inspection [40]. Electrochemical techniques, while not commonly applied in-field, have proven useful in laboratory settings for evaluating inhibitor performance and coating degradation [41]. SEM-EDS is often used to support root-cause failure analysis by identifying salt entrapment, intergranular attack, and complex deposit composition [42].

Figure 10. Pitting and filiform corrosion visible along rivet lines and the aluminium skin surface of a military aircraft. Image source: Aero Corner.

Surveillance towers, radar systems, and other fixed installations. Military systems and installations are highly vulnerable to atmospheric corrosion, particularly in open or coastal environments. Stainless steel and galvanised steel structural supports are susceptible to corrosion driven by the combined effects of salt aerosols, biofilm formation, and UV degradation of protective coatings. Biofilms can trap moisture and salts on surfaces, reducing the effectiveness of passive films and catalysing localised electrochemical reactions that encourage corrosion [43]. Visual inspection is widely used, supported increasingly by the use of UAV-mounted cameras for general structural assessments [14]. Corrosion coupons installed at different elevations and orientations on fixed structures provide valuable site-specific data, especially where environmental severity varies by height and orientation. XRF supports material verification and early identification of alloying element loss or corrosion product build-up, particularly on stainless or galvanised steels [24]. For infrastructure affected by MIC or coating delamination, SEM-EDS enables detailed compositional mapping of localised attack zones and microbial influence [43].

Munitions depots and equipment storage facilities. Older or non-climate-controlled depots and storage warehouses frequently face high relative humidity and poor ventilation. These conditions promote uniform corrosion on unprotected metallic surfaces such as weapon barrels, ammunition casings, and steel shelving. Condensation events driven by daily temperature shifts further increase surface moisture, creating a conducive environment for MIC and the formation of corrosive deposit [12]. Visual inspection remains essential for identifying early signs of surface rust or paint failure on stored weapons and ammunition. Corrosion coupons provide a cost-effective means of tracking long-term degradation trends in representative areas [24]. Facilities equipped with electrochemical sensors or humidity loggers benefit from real-time monitoring of critical thresholds. In cases where unexpected degradation occurs, SEM-EDS is used to analyse corrosion debris or MIC-related by-products with high precision [43].

Figure 1. Surface corrosion visible on multiple rifles stored outdoors without adequate environmental protection. Image source: Zerust Rust Prevention.

Ultimately, a robust corrosion detection strategy will enhance the RBAF's capacity to perform informed and evidence-based decisions on the repair, replacement, and allocation of assets. When combined with environmental knowledge, platform-specific risk profiling, and consistent inspection intervals, detection becomes a powerful enabler of proactive maintenance. This approach not only reduces life-cycle expenses but also reinforces operational readiness, which is critical for a tropical, corrosion-prone operational environment.

5.0 ADDRESSING CHALLENGES IN CORROSION DETECTION IN THE ROYAL BRUNEI ARMED FORCES

Given its critical role in safeguarding operational integrity, corrosion detection within the RBAF presents opportunities for improvements in meeting evolving operational demands. Existing frameworks often focus more on mitigation and monitoring and less on early-stage detection strategies. As previously highlighted, early corrosion detection is essential to preventing irreversible damage, especially under Brunei Darussalam's aggressive tropical climate.

Gap in data. Current corrosion maintenance policies largely rely on international standards and guidelines developed by original equipment manufacturers (OEMs). These guidelines may not account for the local climate which features year-round humidity, copious salt exposure, and intense biological activity. Unpredicted high corrosion rates frequently lead to unplanned early maintenance to prevent severe structural degradation. Consequently, failure prediction for military assets remains uncertain due to the absence of long-term, environment-specific corrosion rate benchmarks, and this adversely hinders accurate service life prediction and risk-based planning.

Gap in technology. Defence platforms and assets continue to rely heavily on manual visual inspections. While valuable as a baseline tool, visual methods are limited in scope and cannot reliably identify subsurface or early-stage corrosion. Advanced tools such as embedded electrochemical sensors and probes have yet to be integrated into asset design or maintenance planning [15]. This restricts the RBAF's ability to shift from reactive maintenance to proactive and data-driven maintenance.

Gap in expertise. Addressing corrosion effectively requires not just tools and protocols but also skilled personnel capable of interpreting complex diagnostic results. While RBAF technical personnel are well-trained in general engineering and maintenance roles, there is a notable shortage of specialists in corrosion science. Expertise remains limited in fields such as electrochemical diagnostics, sensor calibration, SEM-EDS interpretation, and failure forensics. This knowledge gap delays root-cause analyses and impedes the adoption of more advanced, predictive approaches to corrosion management. Current maintenance practices generally follow a tiered structure: first-line involving visual inspections, second-line involving minor repairs, and third-line and fourth-line involving major repairs and overhauls. A potential policy shift towards outsourcing higher-level maintenance to external contractors may help to fill immediate capability gaps in asset maintenance, but could reduce opportunities for RBAF personnel to develop advanced technical skills. This observation is context-dependent, with its relevance shaped by RBAF policy priorities.

Fragmentation in standard application. Adoption of international standards and guidelines are often implemented generically without modification for the local context. Additionally, the absence of a unified, defence-specific corrosion detection policy has led to inconsistencies in inspection intervals, documentation protocols, and diagnostic procedures across service branches. This lack of integration discourages institutional learning, complicates cross-platform comparisons, and hinders the development of a centralised corrosion intelligence database.

Bridging these gaps requires a paradigm shift from reactive to predictive corrosion management. This involves not only adopting advanced detection technologies but also strengthening institutional knowledge and tailoring corrosion standards and guidelines to Brunei's unique operational environment. The following strategic interventions outline actionable steps toward achieving advancements in corrosion detection practices across the RBAF.

a) Deployment of real-time detection systems

High-risk platforms such as naval hulls and airframes should be equipped with real-time corrosion detection tools. These may include the integration of electrochemical sensors and probes, and humidity monitors. When embedded within structures like ballast tanks, vehicle underbodies, or aircraft shelters, these tools enable early warnings and reduce dependency on periodic inspections [20]. The effectiveness of real-time monitoring can be further enhanced through the application of Artificial Intelligence (AI) and Machine Learning (ML), enabling more accurate corrosion prediction, and subsequently improve the service-life prediction of assets.

b) Establishment of central database with predictive modelling and risk mapping

Localised corrosion data collected from corrosion coupons, SEM-EDS failure analyses, and field environmental sensors should be integrated with AI and ML-based corrosion prediction models within a central database. This repository of data can support the development of Geographical Information System (GIS)-based predictive models that inform site-specific maintenance schedules, material selection, and facility design across airbases, ports, and inland installations, as well as relevant civilian assets to form a more robust database. The database allows for further analysis, such as the formulation of tailored maintenance schedules for individual assets.

c) Development of corrosion science competency

Building internal expertise is essential to sustain advanced detection and prevention efforts. The RBAF is encouraged to invest in certified training for engineers, technicians, and inspectors. Concurrently, partnerships with Institutes of Higher Learning (IHLs) can help embed corrosion diagnostics, electrochemical principles, and failure analysis into military technical education. This dual-track approach will enhance in-house diagnostic capacity and support the long-term institutionalisation of proactive corrosion detection.

6.0 CONCLUSION

Located within a tropical landscape, Brunei Darussalam experiences significant and unique corrosion challenges, with environmental parameters that accelerate both the onset and severity of material degradation across defence platforms. While various corrosion detection methods are available, their effectiveness hinges on appropriate selection, environmental adaptation, and strategic integration. In military settings, where failure can result in mission-critical consequences, visual inspections alone are insufficient. Instead, a layered approach combining real-time electrochemical monitoring, subsurface NDT, material-specific diagnostics (XRF, SEM-EDS), and long-term exposure assessment (corrosion coupons) is essential. Closing capability gaps in RBAF demands investment not just in technology but also in human capital and policy, which can be achieved through building localised datasets, strengthening corrosion diagnostics training and standardising detection practices across to suit Brunei's operational environment. Transforming corrosion practices from reactive to predictive will not only enhance asset longevity but also reinforce the nation's operational resilience in an increasingly complex defence environment.

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About the Author

- ***Major (U) Fatin Nur Hanani binti Hamdani***

She is a Staff Officer Grade 2 for Occupational Health and Safety (OHS) Cell, Inspectorate Unit of the Royal Brunei Air Force (RBAirF). She is actively involved in promoting health and safety initiatives across the unit. With a focus on strengthening safety culture and improving operational well-being, she has introduced several initiatives, including the implementation of solar-powered speed monitoring systems to reduce unsafe driving within the Rimba Air Base premise and the publication of the RBAirF Mind Wellness Guidebook, aimed at enhancing mental health awareness among personnel. Through these initiatives, she continues to support the RBAirF's commitment to a safer, healthier and more resilient force.

STRENGTHENING SAFETY CULTURE IN ROYAL BRUNEI AIR FORCE (RBAirF): FROM COMPLIANCE TO COMMITMENT

Major (U) Fatin Nur Hanani binti Hamdani
Inspectorate Unit, Royal Brunei Air Force

ABSTRACT

Safety is a critical component of operational effectiveness within military organizations, particularly in high-risk environments such as the Royal Brunei Air Force (RBAirF). This study examines the current safety culture in the RBAirF, focusing on the transition from a compliance-based approach to a commitment-based safety culture. A quantitative survey was conducted among 493 personnel across different ranks and service years to assess attitudes, behaviours, and perceptions of safety. The results indicate that while the majority of personnel demonstrate commitment-based behaviours such as personal responsibility, motivation, and unsupervised adherence, there are still indications of compliance-driven behaviour, particularly in formal safety inspections and routine procedures. Results also reveals that higher-ranked personnel and those with longer service exhibit stronger commitment, whereas lower-ranked and less experienced personnel show greater reliance on procedural compliance. These findings highlight the need for targeted training, leadership reinforcement, and risk-focused safety processes to further strengthen a proactive safety culture. The study concludes that RBAirF has a strong foundation for commitment-based safety, but ongoing interventions are necessary to fully embed safety as a shared organizational value rather than a task-driven requirement.

Keywords:
Safety Culture, Tick-Box Culture, Compliance, Commitment, Safety Attitudes, Leadership.

1.0 INTRODUCTION

In any military organisation, safety is a key component of operational effectiveness. Safety enables military to maintain its combat readiness capability and welfare of the personnel within the Royal Brunei Air Force (RBAirF). Its importance goes beyond adhering to regulations and policies. Military operations tend to be operated within high-risk environments and air force personnel are constantly exposed to risks related to aircraft operations, maintenance activities, munitions handling as well as other environmental stressors. Operating in fast operational tempo, vigorous mission requirements and airspace complexity necessitate personnel's absolute adherence to a strong Health, Safety and Environment (HSE) principles. The mission success, operation capability as well as preservation of life and assets can be jeopardised by a single slip-up in the safety discipline. Therefore, it is necessary for operational requirement to include safety management in their planning, execution and post-mission review rather than being a support function.

Upholding a robust safety culture in the RBAirF guarantees that every operation, whether in peacetime or conflict, is carried out safely, effectively and sustainably by being consistent with the RBAirF's core values of "Service Above Self, Teamwork and Excellence". Even though safety compliance is the cornerstone of any successful system, true safety excellence goes beyond following procedures and checklists. A true safety culture in an air force is when there is a collective mindset within the organisation that safety is a personal responsibility. Thus, it must be embedded in personnel daily routines, decision making and leadership practices. While the Ministry of Defence has set enforcements through policy such as **Figure 1**, airmen and airwomen need to uphold the tone and extend it through mutual responsibility and professionalism. This could shift the air force from compliance to commitment when safety becomes a habit in their workplace.

KESIHATAN DAN KESELMATAN KERJA (KKK)
KEMENTERIAN PERTAHANAN

HASRAT

1. Menyedari bahawa tenaga kerja ada kalanya menghadapi risiko yang tinggi dan persekitaran yang berbahaya, memastikan kesihatan dan keselamatan semua individu adalah sangat penting bagi Kementerian Pertahanan dan Angkatan Bersenjata Diraja Brunei. Dengan matlamat untuk menyediakan persekitaran kerja yang sihat dan selamat bagi semua anggota tentera, kakitangan awam, kontraktor dan pelawat, Kementerian Pertahanan akan memastikan risiko kepada kesihatan dan keselamatan di tempat kerja diuruskan dengan baik melalui kaedah "Serendah Boleh Dipraktikkan (*As Low As Reasonably Practicable - ALARP*)". Dasar Kesihatan dan Keselamatan Kerja Kementerian Pertahanan akan mendokong dan mematuhi sepenuhnya Perintah Keselamatan dan Kesihatan di Tempat Kerja 2009 Negara Brunei Darussalam dan peruntukan undang-undang lain yang berkaitan dengannya.

KOMITMEN

2. Kementerian Pertahanan adalah komited dalam membangunkan kesedaran budaya keselamatan yang kukuh di mana setiap individu mesti memiliki rasa bertanggungjawab terhadap keselamatan orang disekeliling dan diri sendiri dengan:

a. Melaksanakan Sistem Pengurusan Kesihatan dan Keselamatan Pekerjaan;

b. Mempertimbangkan secara serius faktor kesihatan dan keselamatan dalam setiap perancangan dan perlaksanaan aktiviti;

c. Meneliti pelan pencegahan insiden dan prosedur tindak balas kecemasan secara berterusan;

d. Memastikan ketersediaan peralatan/ kelengkapan kerja yang selamat;

e. Membuat penilaian risiko ke atas semua aktiviti yang berisiko tinggi dan berpotensi merbahaya di tempat kerja;

f. Menyediakan Latihan Kesihatan dan Keselamatan Kerja yang bersesuaian secara berterusan; dan

g. Menilai prestasi Kesihatan dan Keselamatan Kerja dari masa ke semasa.

AKAUNTABILITI DAN TANGGUNGJAWAB

3. Kesihatan dan Keselamatan Kerja adalah tanggungjawab bersama semua anggota-anggota tentera mahupun kakitangan-kakitangan awam di mana:

a. Pemerintah-Pemerintah, Ketua-ketua Jabatan dan *Line Managers* perlu menunjukkan kepimpinan dan komitmen yang nyata terhadap Kesihatan dan Keselamatan Kerja;

b. Semua anggota ABDB dan warga Kementerian Pertahanan bertanggungjawab atas keselamatan individu dan sentiasa mematuhi prosedur serta dasar Kesihatan dan Keselamatan Kerja;

c. Semua anggota ABDB dan warga Kementerian Pertahanan bertanggungjawab untuk memberi sokongan yang berterusan kepada pemimpin dalam memenuhi tanggungjawab Kesihatan dan Keselamatan Kerja; dan

d. Semua anggota ABDB dan warga Kementerian Pertahanan hendaklah melaporkan sebarang isu yang membimbangkan yang boleh menimbulkan bahaya di tempat kerja melalui rangkaian Pengurusan Kesihatan dan Keselamatan Kerja.

KEWAJIBAN UNDANG-UNDANG

4. Semua anggota tentera dan kakitangan-kakitangan awam hendaklah mematuhi piawaian Kesihatan dan Keselamatan Kerja Negara Brunei Darussalam dimana bersesuaian semasa berada diluar negara bagi tugas – tugas rasmi dan juga mematuhi syarat-syarat negara tuan rumah.

5. Semua kontraktor dan pelawat hendaklah mematuhi peraturan Kesihatan dan Keselamatan Kerja Kementerian Pertahanan.

6. Atas asas keselamatan negara, pengecualian dan pembatalan yang khusus terhadap dasar ini boleh diperkenalkan jika diperlukan.

25 Rejab 1445/
06 Februari 2024

BRIGEDIER JENERAL (B) DATO SERI PAHLAWAN
HAJI ALIRUPENDI BIN HAJI PERUDIN
Setiausaha Tetap Kementerian Pertahanan

OCCUPATIONAL HEALTH AND SAFETY (OHS) POLICY
MINISTRY OF DEFENCE

INTENT

1. Realising that the workforce at times operates in an extremely risky and hazardous environment, ensuring the health and safety of all individuals is paramount for the Ministry of Defence and the Royal Brunei Armed Forces. With its aim to provide everyone in the organisation with a healthy and safe working environment, the Ministry of Defence will ensure the risks to health and safety in the workplace are managed "As Low As Reasonably Practicable" (ALARP). The Ministry of Defence Occupational Health and Safety Policy shall support and comply with Brunei Darussalam's Safety and Health Order 2009 and other national statutory provisions.

COMMITMENT

2. The Ministry of Defence is committed to building a strong safety culture where everyone must have a strong sense of ownership for his safety and the safety of those around them by:

a. Implementing Occupational Health and Safety Management System;

b. Considering seriously the health and safety factors in every planning and decision of activity;

c. Continuously reviewing the Incident Prevention Plans and the Emergency Response Procedures;

d. Ensuring the availability of safe work equipment;

e. Carrying out risk assessments on all extreme risk activities and potential hazards in the workplace;

f. Continuously providing appropriate Occupational Health and Safety Training; and

g. Evaluating Occupational Health and Safety Performance.

ACCOUNTABILITY AND RESPONSIBILITY

3. Occupational Health and Safety is a shared responsibility within the workforce for both military personnel and civilian employees where:

a. Commanders and Head of Departments must demonstrate visible leadership and commitment towards Occupational Health and Safety;

b. All personnel in the Ministry of Defence take accountability and responsibility for their safety and behave in accordance with the Occupational Health and Safety policies and procedures;

c. All personnel in the Ministry of Defence are responsible for supporting each other and the senior leader to meet all work health and safety responsibilities; and

d. All personnel in the Ministry of Defence must report through the Occupational Health and Safety management chain on any concerns that may create danger in the workplace.

LEGAL OBLIGATIONS

4. When abroad for official duties, all military personnel and civilian employees will apply Brunei Darussalam's health and safety standards whenever practical and comply with the host nation's health and safety requirements.

5. All contractors and visitors must comply with the Ministry of Defence's Occupational Health and Safety Procedures.

6. On the grounds of national security, specific exemptions and disapplication to this policy may be introduced when absolutely essential.

BRIGADIER GENERAL (B) DATO SERI PAHLAWAN
HAJI ALIRUPENDI BIN HAJI PERUDIN
Permanent Secretary of the Ministry of Defence

25 Rajab 1445/
06 February 2024

Figure 1. Ministry of Defence OHS Policy.

2.0 AIMS

This paper aims to assess the current safety culture in the RBAirF, determine differences in safety perception across rank and service years and to identify areas for improvement in transitioning from compliance to commitment.

3.0 CONCEPTUAL FRAMEWORK

This subsection outlines the conceptual distinction between compliance and commitment which underpins the analysis of safety practices within the RBAirF.

3.1 | From Compliance to Commitment

Compliance in terms of safety is done to ensure personnel fulfill the bare minimum of legal and policy obligations. Therefore, it is characterised by rules-driven, focus on inspections and dependent on checklists as its main focus is to follow established manuals and standards [1]. Although this way offers consistency, it can be regarded as negative indicators of safety culture as organisations tend to be reactive where risks are addressed only after they are arisen or when discovered during audits and inspections. In applying the safety culture ladder in **Figure 2**, the RBAirF should reflect themselves where they are now and what they want to achieve as this will help reflects the levels of the RBAirF's maturity in safety [2]. Although, being compliance-based may preserves structure and discipline in military, but it may limit individual initiative and ownership since safety is seen as a task rather than a shared responsibility.

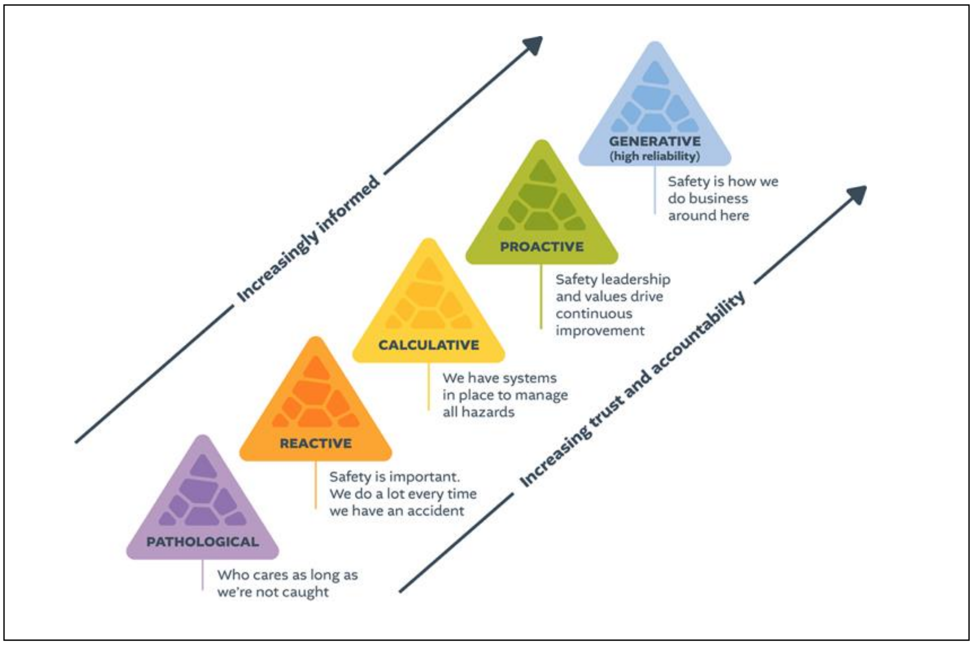

Figure 2. Safety Culture Ladder.

On the other hand, commitment-based safety is based on individual accountability, open communication and the conduct of exemplary leadership behaviour, which goes beyond legal and regulatory requirement. According to **Figure 2**, engagement and safety performance increases when safety is taken as a shared value whereby personnel and management in the organisation are being proactive and everyone assumes safety responsibility as a fundamental duty [3, 4].

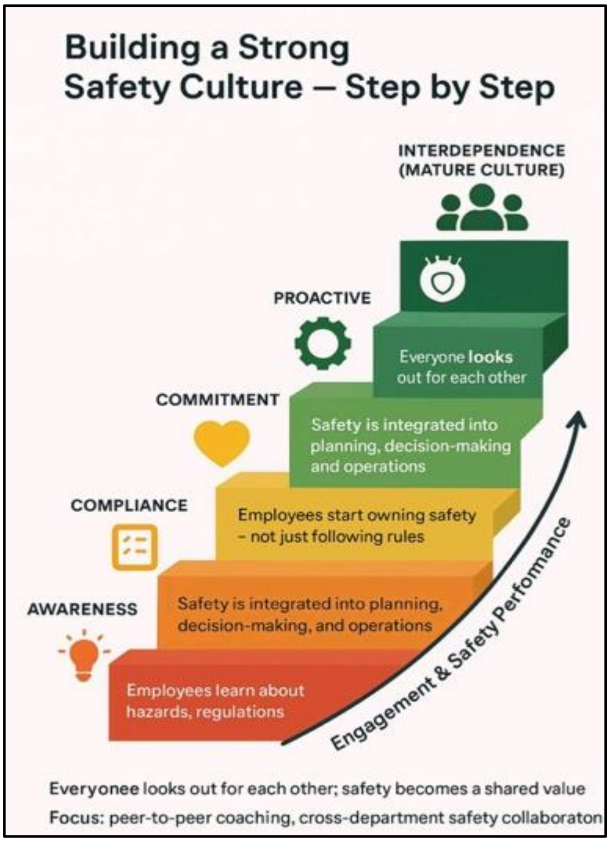

Figure 3. Building a Strong Safety Culture.

Engagement and safety performance are fueled by motivation and commitment to protecting lives, assets and operational capability rather than depending on external enforcement. A basic example is where leaders show their dedication by consistently prioritising safety in their actions or decisions, and personnel under their responsibility supports this by holding each other accountable and taking pride in their work.

3.2 | Tick-Box Culture and Its impact

Although compliance offers structure and accountability, relying too much on it can lead to a "tick in the box" culture in which fulfilling key performance indicators (KPIs), audit requirements and passing inspections takes precedence over actually managing risks. This is concerning as personnel may act in these situations out of duty rather than understanding its importance and risks, resulted in complacency and reduce vigilance. A tick in the box culture believes that compliance is an end goal rather than controlling risks [5]. This mentality may diminish critical thinking, weakens safety performance and inherently, reduce military operational effectiveness as hazards are constantly evolving.

An example is induction safety brief that is done annually across all departments in the RBAirF whereby in order to satisfy compliance requirements, personnel show up for the sessions and simply sign the attendance sheet. However, the information shared might not result in safer behaviour in their workplace without any engagement, understanding or application beyond induction brief. As such, this embodies the tick in a box culture in which presence is recorded but mindset remains unchanged. Whereas, in commitment-based environment, personnel actively participate, ask questions and apply lessons learnt to their tasks and hence, transitioning from performing safety as a task to regard safety as a value.

4.0 METHODOLOGY

This section outlines the research approach adopted to assess safety attitudes and behaviours within the RBAirF, focusing on the distinction between compliance-driven and commitment-based safety practices.

4.1 | Research Design

This study employed a quantitative research design using a structured survey questionnaire to assess the current safety attitudes and behaviours across the RBAirF. A quantitative approach was chosen because it allows for systematic measurement of personnel perceptions to enable a clear comparison indication between compliance and commitment-based safety. The survey questionnaire consisted of 11 questions designed to measure participants' understanding on safety and their motivations for adhering to safety rules and whether their behaviours reflected more on compliance driven or commitment tendencies. The survey is designed to support the paper's aim in identifying organisational safety tendencies by measuring patterns across ranks and service years. It provides a foundation for analysing the safety culture and identify areas that require intervention or leadership reinforcement. Several key questions include how important do they believe safety is in their daily duties, whether participants believe maintaining safety is a personal responsibility, checking if personnel agree safety checks are done only to meet requirements and personnel adhere to safety rules even when no one is watching.

4.2 | Participants

A total of voluntary 493 personnel across officers, non-commissioned officer (NCO) and other ranks participated in the questionnaires. Thus, providing a broad representation of perspectives across the organisation and identifies potential gaps between policy expectations. Rank and service years were intentionally included as demographic variables to examine whether perceptions of safety differ across levels of leadership experience and operational exposure. This enables the analysis of potential differences between newer personnel and longer-serving members.

This subheading presents the finding from the survey conducted among RBAirF personnel. A summary of respondent demographics is shown in **Figure 4**. The distribution illustrates the representation across ranks and years of service.

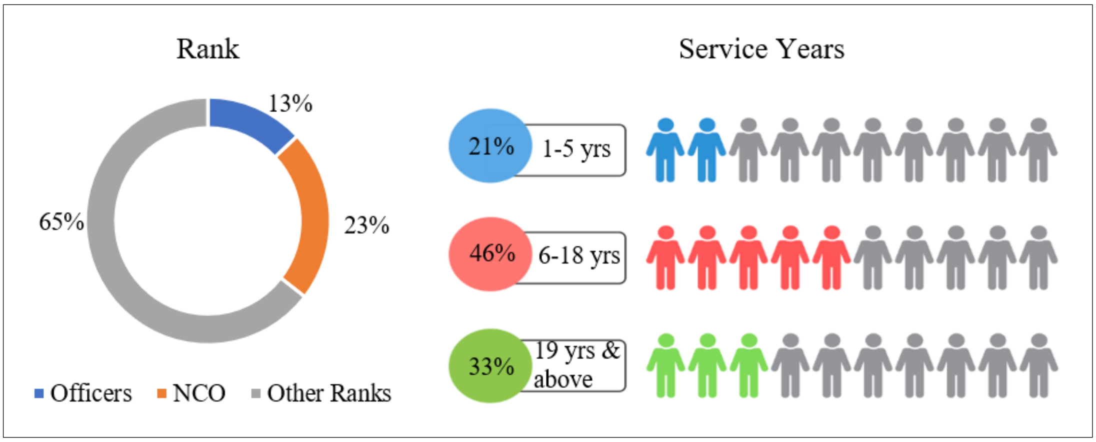

Figure 4. Demographic Distribution of Respondents.

5.0 RESULTS AND DISCUSSION

This section presents the survey findings and discusses their implications in relation to the transition from a compliance-based safety culture towards a commitment-driven approach within the RBAirF.

The survey identifies several strong indication of positive safety cultures within the organisation whereby respondents demonstrated high awareness of established safety procedures, suggesting that foundational safety knowledge is well understood across the RBAirF. For example, in Question 3 – 'How important do you believe safety is in your daily duties?', 430 out of 493 respondents rated safety as very important. Moreover, strong adherence to operational standards indicates that personnel are consistent in following guidelines and procedures which can be seen in Question 10 – 'Personnel adherence to safety rules even when no one is watching', 53% of the respondents strongly agreed and 32% agreed that personnel adhere to safety practices even when unsupervised. Furthermore, Question 5 – 'Do you believe that maintaining safety is a personal responsibility?' shows that 95% of the participants recognise safety as a personal responsibility, thus, supports proactive engagement in hazard identification and consistent reporting. This reflects a functional reporting mechanism that is functional and a workplace that recognises the importance of hazard identification.

The results demonstrate a strong foundation of strong compliance supported by procedures, strong leadership influence and effective reporting system. However, commitment-based behaviours are still uneven across the organisation as shown in **Figure 5**. Transitioning from a compliance-oriented culture towards commitment-driven will require efforts focusing on psychological safety, enhancing empowerment and fostering safety ownership at all levels of the RBAirF.

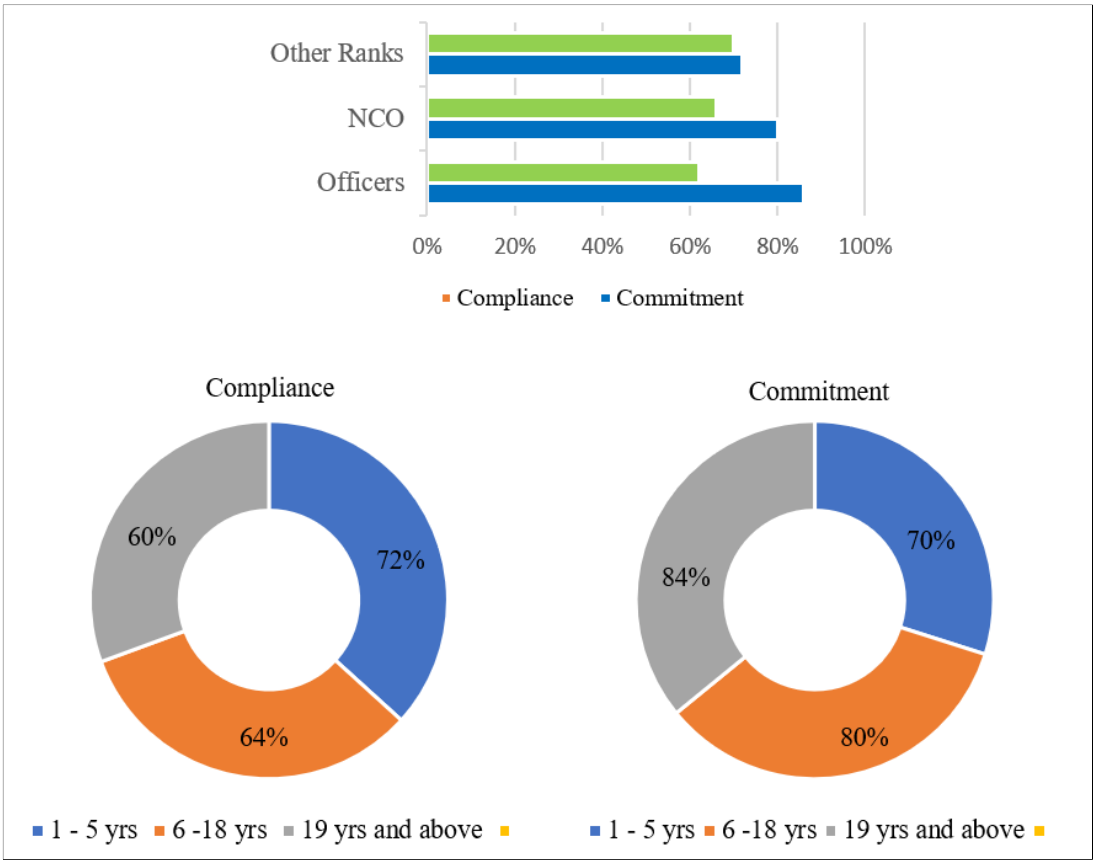

Figure 5. Survey Results.

On the other hand, the responses regarding safety checks reveal a clear contradiction within the organisation's safety culture. While majority of the personnel demonstrate strong personal commitment to safety, more than half of the participants indicate that safety checks are conducted primarily to satisfy requirements. This suggests that the act of doing safety is perceived as a task to be completed. Hence, this reveals the "tick-box" culture in inspection and reporting mechanisms. While personnel care about safety, they see safety processes as routine and lacking purpose. Personnel may be motivated, but the environment of the RBAirF have been shaped by rigid compliance expectations that reinforces procedural conformity than risk-based safety practice.

Several items highlighted opportunities for improving commitment driven safety culture. When asked which best described their reason for following safety rules, a small proportion of respondents (7%) indicated that it is due to the requirement by regulations, while a few others cited a fear of disciplinary action or it's an expectation from their officers, suggesting some personnel's adherence is driven by compliance. Similarly, in Question 4 – 'I clearly understand the safety policies and procedures in my unit', most respondents reported a clear understanding on this, however, a small number indicated uncertainty which reflects that not all personnel fully internalise safety guidance. Moreover, responses to Question 9 – 'Safety checks are done only to meet requirements' revealed 121 participants strongly agree and 142 participants agree to the above. This shows a tick-box culture and highlights areas where empowerment, psychological safety and proactive engagement can be strengthened to reinforce commitment-based safety behaviours across all ranks.

In a broader sense, this highlights the challenges faced by the RBAirF for transitioning from a system that measures primarily through compliance indicators to proactive hazard recognition. However, it is important to note that the organisation is on the right path as there is an existence of commitment from the personnel, but reforms in processes are required in aligning with safety values. This can be done with involvement of leadership, improving the quality and purpose of inspections and shifting towards risks-based evaluation to ensure organisational system fully support the strong commitment demonstrated by the airmen and airwomen [5].

6.0 CONCLUSION

In conclusion, the survey results provide a clear overview of the safety culture within the RBAirF. Section 2.2 highlighted the demographic profile of participants, showing a balanced mix of rank and service years in ensuring a diverse perspective in responses. The results and discussion in section 3.0 revealed that majority of personnel demonstrate a commitment-based safety approach especially in personal responsibility, deep-rooted motivation and adherence to procedures without supervision. However, there are indications of compliance-driven behaviour mainly on formal safety checks, suggesting areas where procedural compliance may be followed more than proactive safety engagement. Collectively, the findings indicate a predominantly positive safety culture but highlight specific areas where reinforcement and continuous engagement could further strengthen proactive safety behaviours across all ranks and experience levels.

7.0 RECOMMENDATIONS

Based on the survey findings, several actions are recommended to strengthen the transition from a compliance-based safety culture within the RBAirF. These recommendations focus on enhancing proactive behaviour, improving organisational systems and reinforcing leadership influence.

In addressing these gaps, RBAirF should enhance leadership engagement. Consistent involvement from leaders is essential in shaping how safety is perceived across ranks [6]. Leaders must not only enforce standards, but actively participate in day-to-day safety conversations, conduct routing engagement walkabout and create opportunities for open dialogue. When leaders show genuine interest in safety beyond procedural compliance, it reflects a clear signal that safety is a shared organisational value than a requirement. This engagement would also build psychological safety, encouraging personnel to voice concern, provide feedback and voice up any unsafe actions without fear of repercussions.

In addition, enhancing training and competency development is also recommended particularly in reinforcing internalised safety values rather than procedural compliance. Training programmes should incorporate scenario-based learning, reflective discussions and practical simulations allowing personnel to demonstrate safety ownership without the presence of authority figures. This approach aligns with the survey’s aim of assessing deep-rooted motivation and personnel responsibility, bridging the gap between stated commitment and observed practice.

Furthermore, organisational systems should be refined to support sustained behavioural reliability, including implementing routine quality checks of safety processes, conducting periodic behavioural audits and ensuring feedback are accessible and non-punitive [7]. These mechanisms may help to identify recurring issues such as inconsistent safety checks and allow corrective actions to be embedded into operational planning. Integrating these insights into ongoing safety performance reviews will ensure that cultural improvements are continuously monitored.

In general, these recommendations aim to reinforce the organisation's existing strengths while addressing areas where compliance behaviour persists. By improving supervisory structures, enhancing behavioural-based training and institutionalising robust monitoring mechanisms, the organisation can strengthen its commitment-based safety culture and ensure greater consistency between personnel attitudes and operational behaviour.

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About the Author

- ***Muhammad Amirul Afiq bin Ramli***

  He is an Electrical and Electronic Engineering graduate from Universiti Teknologi Brunei (UTB) who joined CSTRAD in 2021 and is now a Research Officer in Centre of Science and Technology Research and Development (CSTRAD) Research & Development (R&D) under Sensors & Mechatronics Cluster.

OVERVIEW OF ADDITIVE MANUFACTURING (3D PRINTING) TECHNOLOGIES FOR MILITARY INDUSTRIES

Muhammad Amirul Afiq bin Ramli
Centre of Science and Technology Research and Development (CSTRAD)
Ministry of Defence

ABSTRACT

This paper provides an overview on the 3 commonly used Additive Manufacturing (AM) technologies that is used today namely Material Extrusion, Vat Photopolymerization and Powder Bed Fusion. The applications of AM in the Aerospace, Space, Medical, Construction and Military are reviewed. A more in-depth review for military application was done especially on the use of the AM technology by the US and UK forces. Other than application, this paper also provides an outlook on the challenges that come with the AM technology, future outlook and the potential utilization of the AM in the Industrial Revolution 5.0.

Keywords:
Additive Manufacturing, 3D Printing, FDM, SLS, SLM, EBM, Military, Industrial Revolution 5.0, Customization

1.0 INTRODUCTION

Additive Manufacturing (AM) or widely known as 3D Printing, is not a new technology. While Hideo Kodama from Japan first described a photopolymer-based rapid prototyping system in 1980-1981 [**1**], however, it was first commercialized by Charles Hull in 1983 and was patented in 1986 [**2**]. This AM technology is in the form of stereolithography (SLA) and is based on photosensitive UV resin. Today, there are more material options that is available to be used for AM ranging from plastics to metals and composites [**3**] and these materials are applicable for wide range of industries from normal consumers to industries [**4**]. A more in depth look into military application and adoption of AM technology are given to provide an overview on how the AM technology has been adopted and the potential use of this AM technology for military application. This paper also discussed on the challenges that came with AM, future outlooks of the AM industry and the potential AM technologies could offer in the future.

2.0 3D PRINTING TECHNOLOGIES

Since 1980s, the AM industry starts to diversify with the additions of few new technologies such as Fused Deposition Modelling (FDM) invented and patented by Scott Crump in 1989 [5], commercialized in 1992 by Stratasys and Direct Metal Laser Sintering (DMLS) which is patented in 1994 and commercialize in 1995.

As of today, according to the ASTM F42 standards [6], the main AM categories are Material Extrusion, Vat Photopolymerization, Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Binder Jetting (BJ), Sheet lamination and Material jetting. However, the mostly used technology as of today are Material Extrusion for the mainstream market, Vat Photopolymerization for the industrial and mainstream market and PBF mostly for industrial grade print which contribute to more than 32.1% of the whole AM market share [7].

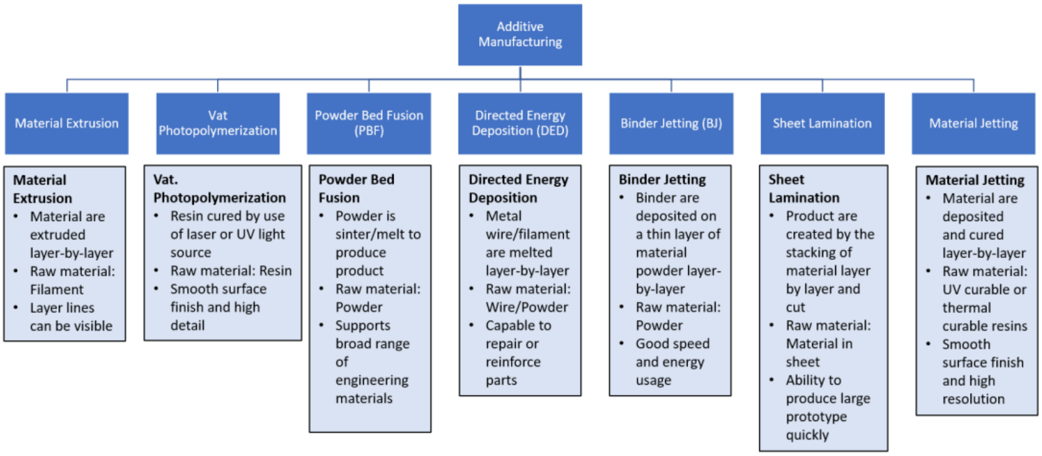

Figure 1. Outline of additive manufacturing technologies.

Material Extrusion

Material extrusion technology, primarily Fused Deposition Modelling (FDM) is the most accessible and cost-effective technology for many applications.

For FDM or Filament Fused Fabrication (FFF), the printing material is in a form of filament which are fed into the printer head to be melted and extruded layer by layer on to the build plate. There are two main types of FDM printers which is Bowden type and direct drive. These refers to the way the material is being fed onto the printer head.

Bowden type printers are one of the common types of printer for FDM. Bowden type printer have its extruder motor (the motor that feed the filament to the print head) placed along the path of the printer feed line and not directly mounted on the print head itself. This enables the print head to be lighter and less sturdy gantry requirement which makes the setup simpler and cheaper. This means that the Bowden type printer would need a longer guiding PTFE tube from the extruder to the print head [8,9].

Direct drive printer is opposite to Bowden type printer. Direct drive printer has its extruder motor mounted on the print head which almost eliminates the requirement for a PTFE tube between the extruder and the print head. This however come at a cost of a heavier print head setup [8,9]. By having a shorter path between the extruder and the print head, direct drive type printer has the advantage of being able to accept more material selection compared to Bowden type printers. These materials range from a simple PLA to engineering grade material such as PEEK.

For material extrusion technology, this AM technology is considered to be the simplest and requiring minimum space requirement and hence it is the widely used AM technology for industries and consumers. With the simple setup of the printer, it does have a down fall especially on the strength of the printed material which tends to be anisotropic. Users of the printer needs to be aware on the print orientations to ensure strength for the applications [10]. With printing orientation, another issues that are faced by the material extrusion technology are the requirement to print support structure while printing this is because the printer could not extrude the print material when the print part is suspended. Printing support structure can be time consuming and could take as much as half (or more than half) of the estimated total printing time depending on the printed part and its orientation [11].

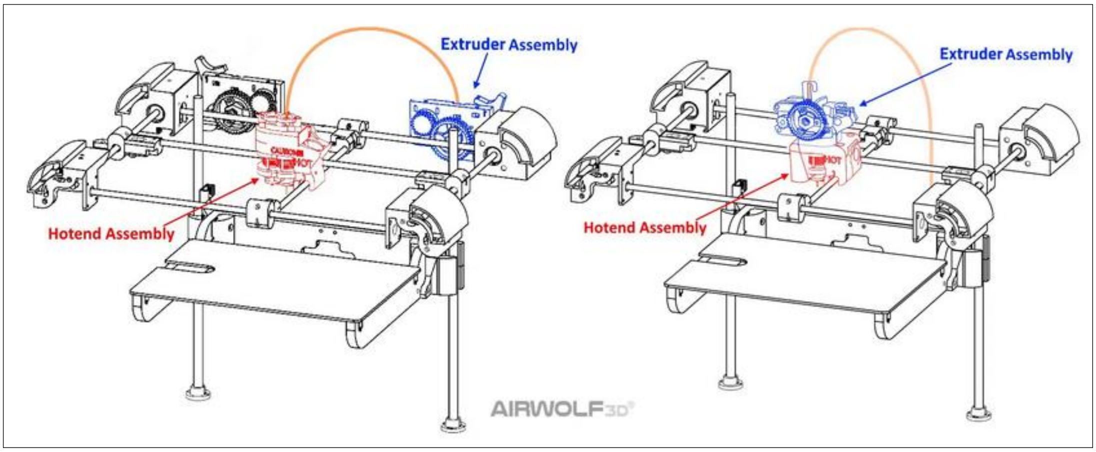

Figure 2. Difference between Bowden type (left) and Direct drive type (right) FDM printer [8].

Vat Photopolymerization

Vat Photopolymerization is also another type of AM that are widely used. Vat Photopolymerization can be divided into three main types: Stereolithography (SLA), Digital Light Processing (DLP) and Masked Stereolithography (MSLA) [12].

Vat Photopolymerization uses a light source to cure the UV sensitive resin. This resin is cured and raised layer-by-layer to produce the final product.

SLA is the oldest AM technology and it uses a laser to cure the resin in the resin pool to trace the cross-section of the printed part layer-by-layer. This results in the slowest printing speed among the vat photopolymerization [13]. DLP uses a light projector to cure the resin and the whole layer is cured in one go making it the fastest of the three. This speed is most noticeable in a large print cross-section. MSLA on the other hand utilizes an LCD screen to mask the UV light source to trace the cross-section of the printed part. Comparing the three technologies, MSLA offers excellent detail and accuracy with XY resolution of 25 to 75 microns for the high-end printers with printing speed positioned between the SLA and DLP [14].

Parts produced by Vat Polymerization have a smooth finish with minimal layer lines and are able to print transparent products. This technology is also capable of producing a highly detailed print due to its high resolution and it also has better dimensional accuracy compared to FDM. Although most standard resin materials are brittle, today the types of resins are being improved and some resins are engineering grade which offer improved mechanical properties. Printed parts, however, do require post processing in the form of additional UV curing which helps the product achieve its full strength and stability [15]. UV resins also experience degradation over time and working with uncured liquid resin requires careful handling and proper disposal as liquid resin can cause serious irritation if mishandled [4,16].

Figure 3. An example of transparent print produced by Vat Photopolymerization [12].

Powder Bed Fusion

Powder Bed Fusion (PBF) is another AM technology that is currently being used. PBF technology involve the use of powder. The three main types of PBF are Selective Laser Sintering (SLS), Selective Laser Melting (SLM) / Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM).

PBF works by spreading a thin layer of the material powder on the build plate and an energy source will fuse the material selectively to trace the cross-section of the printed product layer-by-layer to form the finished product.

For SLS technology, it uses laser to sinter the powder which is typically polymer powder such as nylon in a Nitrogen filled environment (build chamber) [17]. For metals, the SLM/DMLS technology uses a high-power fiber laser to fully melt the metal powder in an Argon or Nitrogen filled build chamber. The metal powder used range from both reactive such as titanium and non-reactive metals such as aluminum and stainless steel. Similar to SLM/DMLS, EBM technology uses a different approach by the use of a high-powered electron beam instead of multiple high-powered laser and it is done in a high temperature, vacuum build chamber. With the high temperature vacuum build chamber, it reduces the residual stress and the thermal gradients on the build product which makes EBM technology to be particularly well-suited for printing reactive metals such as Titanium [18].

3.0 AM MATERIALS

The raw material for AM varies depending on the AM technology used. This ranges from filament, powder and resins for material extrusion, PBF and vat photopolymerization respectively.

Consumer grade material

As FDM (material extrusion technology) is the most widely used polymer/consumer grade printing technology [7], filaments represent a major form of raw material in AM. FDM filament can easily be divided into two main categories which are consumer grade and engineering grade. Consumer grade filaments are readily available, easy to print and suitable for general use. Engineering grade materials, on the other hand, are more expensive, require higher print temperatures and offer superior mechanical properties such as increased strength and heat resistance.

The most widely used consumer grade filaments are Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG) and Acrylonitrile Butadiene Styrene (ABS). PLA offers the best printability (printing temperature 180°C to 220°C) [19], is cost-effective and is biodegradable under industrial composting conditions [20]. PLA is most suited for prints that do not require high strength and are not subjected to high temperature. These applications include indoor home decorations and prototype models that are not used as a functional part. PETG is similar to PLA in terms of ease of printing with just a slight increase in print temperature (220°C to 250°C) [19] and offers a better chemical resistance, durability, temperature resistance and strength compared to PLA. This material is suitable for printing functional parts and mechanical components. ABS print at a temperature similar to PETG (220°C to 250°C) [19] but requires a proper temperature control to prevent warping (print lifting from the print bed); however, it offers a better mechanical strength and heat resistance compared to the other two and hence it is widely used in functional and durable prints.

The second most widely used technology in AM behind FDM is Vat Photopolymerization. Vat Photopolymerization uses resin as the raw material for the print [15]. Standard resin came in different variation and colours. These resins typically are more brittle and is usually used for indoor decorations, figurines and other fine details print that does not require strength.

Engineering material

For FDM, there are a few engineering materials that is available. The most commonly used material is Polyamide (PA) or commonly known as Nylon. Nylon filament prints at a temperature of 250ºC and higher which is the maximum limit to be printed on a consumer grade printer. Nylon filaments specifically PA6 are tend to be more hygroscopic [21] compared to ABS and PETG filaments which means PA6 Nylon would requires a more proper storage with proper desiccation to prevent it from absorbing moisture from the surrounding. Despite the high printing temperature requirement and proper handling and storage of the filament, Nylon generally offers a better toughness, durability, flexibility and impact resistance comparted to ABS or PETG.

Other examples of engineering materials include Polycarbonate (PC), Polyether Ether Ketone (PEEK) and Ultem 9085 (PEI: PC). PC filament is printable on an upgraded consumer grade printer and offers advantages such as higher tensile strength compared to consumer grade filaments, excellent electrical insulation and high impact resistant. PEEK and PEI: PC on the other hand is only printable on industrial grade printers as the printing temperature requirements are above 350ºC, heated bed exceeding 120ºC (depending on material) and the requirement of heated enclosed chamber [22]. These materials are harder to print compared to consumer grade filaments but it offers high temperature resistant (260ºC continuously for PEEK) or flame retardancy for PEI: PC and excellent strength-to-weight ratio which makes it more applicable and widely used in aerospace and medical industries.

For PBF, all print materials are considered to be engineering grade. An example for SLS, the most commonly used print materials are PA12, PA11 and Thermoplastic Polyurethane (TPU). These materials are a polymer and offers improved strength, dimensional accuracy, durability and flexibility compared to consumer grade material. It is widely used in functional prototypes, drone components, protective gears, gaskets, seals and etc. For metal prints, SLM commonly uses Titanium alloys (Ti6Al4V) [23], 316L Stainless Steel, and Aluminium alloy (AlSi10Mg), while EBM primarily uses Titanium alloys (Ti6Al4V), Cobalt Chrome and Nickel Alloy (Inconel 718). These materials are typically applicable for aerospace, automotive, medical and other industrial applications.

For Vat Photopolymerization, engineering grade resin also exist such as tough resin, high temperature resin and ceramic filled resins. These resins have been used in the aerospace and automotive industries primarily for prototyping, tooling and low volume manufacturing. An example application is the use of high temperature resin as a mold for injection molding. Low volume manufacturing sometimes serves as an alternative to traditional manufacturing where customization is a priority and is typically used in a non-critical area of application.

4.0 GENERAL STEPS FOR AM

Regardless of the different type of AM technologies, there is a common flow in all the different technologies. The main process in AM are Computer Aided Drawing (CAD) design, slicing, printing and post processing [24,25].

For CAD Design, there few methods to produce the 3D model. First method is to create a 3D design in a CAD software based on an existing drawing or based on the intended use of the item. There is a huge selection of software that are available that can be used to generate the 3D model and this includes Solidworks, Fusion 360 and Sketch Up. Some of this CAD software features iterative optimization algorithm which reduces material usage while maintaining the designed strength which will eventually reduce the print time require since less material is required [26,27].

Another method that is also widely used as of today is the use Artificial Intelligence (AI) services to convert an image to 3D model. An example of this service is Meshy AI, 3D AI Studio, Tripo AI and Magic 3D. These AI generated models will often require post processing or refinement to ensure precision and functionality.

Lastly, another method to produce a 3D model is by the use of 3D Scanners. This scans the actual object and produce a 3D file that could be printed after post-processing. This is to remove the unwanted surface and refine the produced mesh files. Additionally, 3D scans can also be obtained using LIDAR equipped devices with the appropriate software such as LIDAR equipped smartphone however, accuracy and resolution of this 3D model is lower compared to a proper 3D scanner [28].

Slicing is a term used in AM to convert the 3D model into a code that could be understood by the printer. The slicer software slices the model into thin layers which dictates the layer height of the produced print. Different printer has different slicer software and some slicer are open-source and some are proprietary. Proprietary slicer typically requires licenses and might also require connection to the internet for verification. There is also a cloud-based slicer which eliminates the requirement to process the model locally. Some cloud-based slicer also integrates the control of the printer from the cloud to enable seamless control of the printing process.

After slicing, the produced file is transferred to the printer, this could be by the means of USB drives, internet or cloud. The print time varies according to the size and the complexity of the model. Different printer has different speed capability and different material can only be printed at certain speed which typically sets the limit on how fast the printer could print. A typical print can range from 30 minutes to over few hours.

Once the print is completed, post processing is typically required. Depending on the technology, removal of uncured resin or removal of excess powder would be required directly after printing is completed. The following steps are removal of supports, heat treatments/UV curing and surface finish. Support removal can be as simple as tearing it away from the printed body to as hard as requiring a tool such as pliers, cutters or grinders especially for metal prints with hard to remove internal support. Heat treatment is applicable for metal prints to improve their mechanical properties and relieve internal stresses. For resin print, UV curing is required to fully harden the resins. For surface finish, printed parts are typically sanded, polished, painted or coated to improve their aesthetics, surface quality or the addition of properties such as wear resistance or corrosion protections.

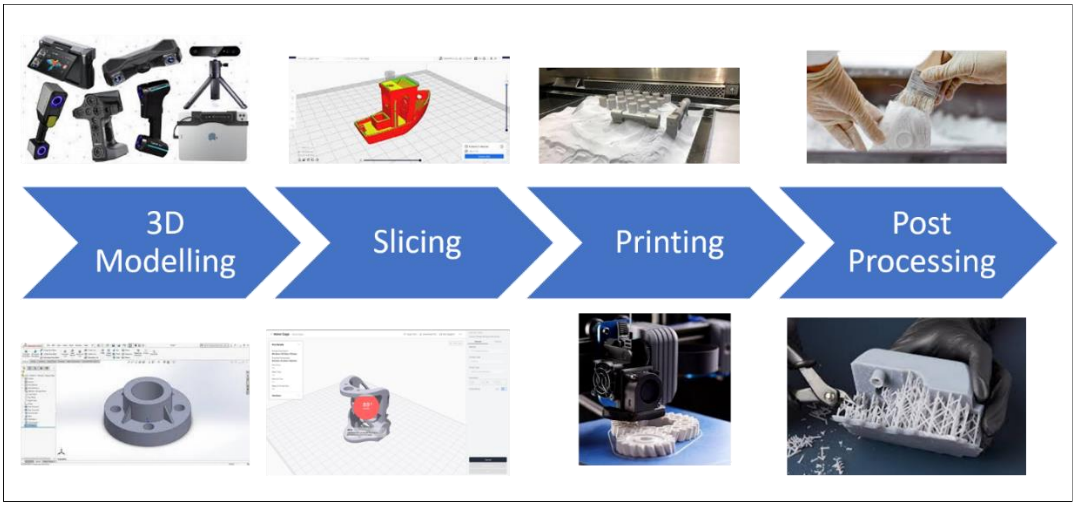

Figure 4. Typical steps in AM.

5.0 APPLICATIONS OF 3D PRINTING

As of today, AM has been tested and being adapted into various different industries such as aerospace, medical, construction, space and defence industries.

Aerospace Industry

An example of application in the aerospace industry was shown by Airbus in the production of a panel for an A320 aircraft which weigh 15% [29,30] less than standard panel and Commercial Aircraft Corporation of China (COMAC) have incorporated the use of 3D printed titanium parts for its C919 aircraft [31]. These 2 companies reported that the use of 3D printing does reduce the overall weight of the aircraft which also aids in the fuel efficiency of the aircraft.

Airbus and Safran also utilized 3D printing for the Arianne 6 rocket consolidating multiple parts to one single components which results in reduced manufacturing time [32] and Space X has used DMLS technology for the production of components for the Raptor engines [33] (rocket engines that powers the Starship spacecraft) and reported that the engine weigh 30% less and improvement in manufacturing time. Recently, Boeing have also utilized AM to improve the lead time for its smaller satellites including over 1,000 radio-frequency components on each of the Military Wideband Global Satcom and is looking to expand the use of this AM technology to its larger satellites which includes the 702-class of satellite [34].

Other than manufacturing, AM are also used for repairs in the aerospace industry where instead of scrapping damaged parts, AM enables the ability to repair the parts which would be a positive on cost saving [35].

Space Industry

For space industry, there have been applications that utilizes 3D printing, as mentioned earlier 3D Printing technology has been used in rocket engines which results in lighter weight. Other than that, Airbus in collaboration with European Space Agency (EASA) has sent a metal 3D printer to the International Space Station (ISS) and it has successfully printed a 9cm x 5cm array of metal components by utilizing direct energy deposition technology [36]. This technology demonstration helps with the ambition of a long-distance manned space mission as replacement could be printed onboard on-demand without requiring to wait for resupply mission.

With this technology, NASA is also exploring on implementing the use for permanent presence on the moon or other planets. Redwire Regolith has successfully demonstrated the printing of simulated lunar dust in microgravity [37] as the construction material for habitats and this means that there is a possibility to establish a moon habitat with only 10% of the material transported from earth and the remaining 90% are utilizing the lunar material.

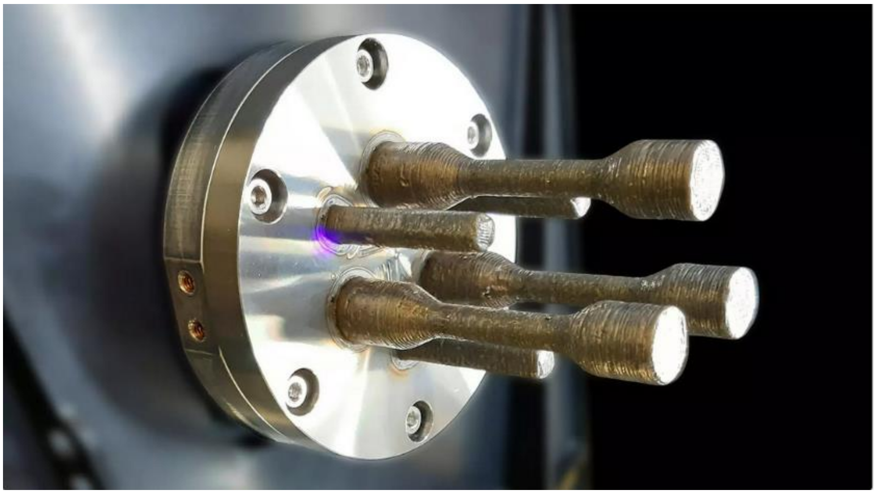

Figure 5. The first metal part printed on the ISS [36].

Medical Industry

In the medical industry, the type of material that are used needs to have biocompatibility to ensure that it will not be rejected by the body. An example of biocompatible material that is widely used are Ti6Al4V [38] which can be printed in a PBF.

Recently, Auxilium Biotechnologies have used 3D printers onboard the ISS to print 8 implantable medical devices simultaneously making it the first medical implant to be manufactured at that scale in microgravity [39]. On other note, skin and cartilage has also been successfully been printed down on earth which could [40] improve wound healing and complicated treatments. In terms of drug delivery, SPRITAM have developed a 3D-Printed pill that easily disintegrate in approximately 11 seconds with a sip of liquid which helps with patients with swallowing difficulties [41]. This pill has been approved by FDA.

3D printing has also been used in the medical industry for creating patient specific implants for example VSP PEEK Cranial Implants which is the world's first FDA approved implant made from PEEK material [42]. These implants are used in cranioplasty procedures and by the end of the same year, the use of this technology enables approximately 40 successful procedures [42]. In dentistry, 3D printing technologies are also used to make crown and bridges [43] and in orthopedics, 3D-printed titanium implants have been used to replace broken bones [44]. In the field of prosthetics, custom 3D printed prosthetics improves fitting and is becoming cost-efficient [45]. An example of this application is as shown by the Department of Veterans Affairs that have used 3D printing to provide an advanced prosthetic care that meet individual patient's needs [46].

Recently, Jerudong Park Medical Centre (JPMC), Brunei, has made a significant milestone in dental care with the launch of Computer Aided-Design (CAD) / Computer-Aided Manufacturing (CAM) system and clear aligner treatment service which sees the use of precise digital scanning, advanced computer-aided design and 3D-Printing. This means an improvement in dental care and convenience in orthodontic options [47].

3D printing has also been utilized in the past to back up the sudden surge in demand during the COVID-19 pandemic including the production of Personal Protective Equipment (PPE) such as respirators, face shield and facemasks [48]. The Fleet Readiness Centre Southeast (FRCSE), US Navy are also involved in the production nasopharyngeal as a nationwide support for COVID-19 containment [49].

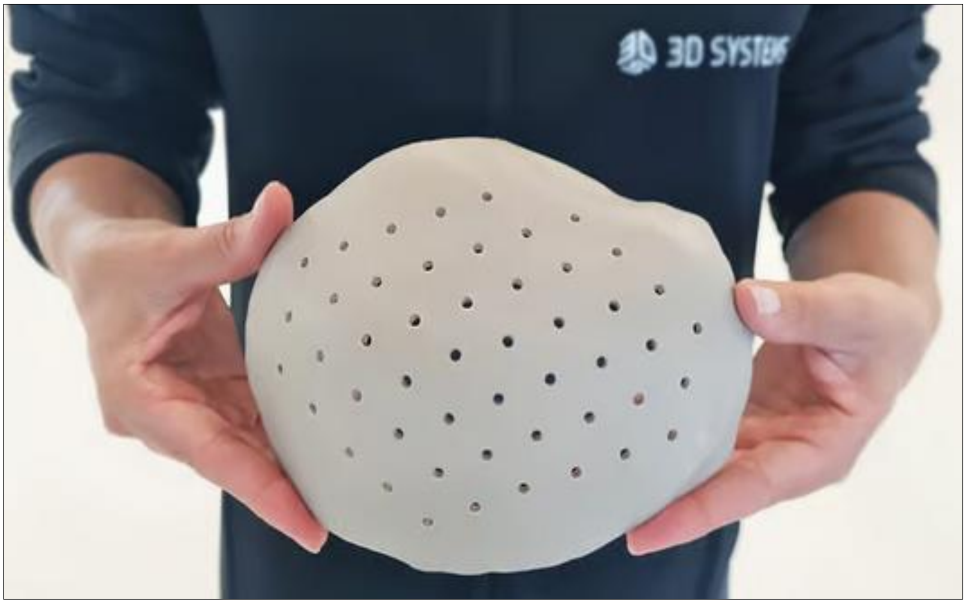

Figure 6. Example of the 3D Printed Cranial Implants [42].

Construction Industry

In terms of construction industry, 3D printing technologies has been adapted in various construction such as "Project Milestone" which is a 94 square meters floor space house made solely by 3D Printing with structural concrete [50]. This technology is also expected to reduce material wastage and labour cost [51] from construction industries by up to 60% and potentially an increase in production of about 50% [52]. According to [53], Department of Defence, US, has also utilize the 3D Printing technology for the construction of three 5,700 square feet barracks, one Fort Bliss, New Mexico which is opened on January 2025 and two in Pershing Heights, Pennsylvania. Each barracks is expected house up to 56 soldiers [53].

Figure 7. An example of the 3D Printed Barracks [53].

Military application

US military and several other militaries around the world have adopted the use of 3D Printing for military applications and these applications are mostly focused on improved logistics faster productions and military capability research and prototyping.

Figure 8. Australian Army installing 3D printed metal wheel bearing cover on M113 Armoured Personnel Vehicle Carrier printed from XSPEE3D printer [54].

Operational Uses of AM in Military

An example of improve logistics is the on-demand printing of spare parts. USS Somerset (LPD 25), a US Amphibious Transport Dock vessel printed a pump gasket using an onboard metal 3D printer for its reverse osmosis system in just a few hours [55] which is an improvement compared to the expected 14 days or more required when waiting for replacement parts. Recently, during exercise Talisman Sabre 2025, the Royal Australian Navy (RAN) have incorporated the use of 3D Printers called the Deployable Additive Manufacturing and Repair Capability (DAMR) which is housed in a shipping container containing various types of 3D printers namely the Prusa Core One, Ultimaker Factor 4, Markforged X7 and in the future Fusion F3 [56]. The RAN managed to print several items during the exercise including communication switches, drone controller, fan bracket and ground pegs for tents [56]. The US Navy, UK Army and Australian Army has been reported to have been validating/utilizing the use of XSPEE3D 3D printer on the front line to print metal parts on demand [54].

This is not only applicable in naval operation; 3D printer has also been used in forward operating bases to print part for vehicle following battle damage to enable vehicle to remain operational for longer [57]. This also includes printing of hard-to-obtain spare parts especially parts that have been discontinued by the original manufacturer [58]. This is being done by the US Army and UK troops. The US Air Force have developed a runway mat that is 3D Printed that enables military aircraft to land and take off from soft ground [59]. In Ukraine, 3D printer is used to produce various parts of UAVs and other military equipment contributing to the rapid assembly and deployment of unmanned system [60].

Figure 9. Example of printers in the RAN's DAMR Prusa Core One (left), Ultimaker Factor 4 (centre), Markforged X7 (right).

Non-Operational Uses of AM in Military

The use of 3D printing in manufacturing are also observed in non-operational military settings. The USS Enterprise (CVN-80), a Gerald R. Ford class aircraft carrier is reportedly been fitted with a valve manifold assembly that is 3D printed [61]. This valve assembly is reported to weigh about 450kg and measured 1.5m [62] in length. According to reports, this could speed up the construction and delivery of the ship to the U.S. Navy. For the US Army, 3D printing has been used to produce parts for ground military vehicle with parts the size of 3 cubic feet being produced on-demand, which reduces the manufacturing time from months to days [61]. A UK defence supplier Babcock International Group similarly have utilized metal 3D Printed part for the British's Army Titan and Trojan fleet's periscope system which is a step forward in the use of additive manufacturing in the defence industry [63]. According to [64] the use of 3D Printing in military logistics and repair improves troops performance and with the use of more 3D printers in the maintenance line could cause significant change to the maintenance organization.

Figure 10. 3D Printed Valve Manifold Assembly for CVN-80 [62].

Military Research

The use of additive manufacturing has also been observed in numerous research which have the potential in military application such as the use of AM in the design of stab resistant armour [65], use of AM in to produce lightweight UAV [66], 3D printed embedded antenna [67], 3D printed anti-drone system [68] and many more. This is because the use of AM is cheaper and more accessible for a prototype production and enables better iteration on the prototype.

According to [69], the US military has over USD70 million budgeted as of 2014 to look into the development of a powered exoskeleton suit to be use for the US military and the project is using the flexibility that is provided by 3D printing to enable rapid prototyping and better iteration process. This project is in line with Industrial Revolution 5.0.

6.0 POTENTIAL APPLICATIONS IN ROYAL BRUNEI ARMED FORCES (RBAF)

In Royal Brunei Armed Forces (RBAF) context, AM technology can be installed onboard the Royal Brunei Navy's (RBN) patrol vessel which would enable RBN to print temporary or permanent replacement part on-demand and carried out the repair while at sea without needing to return to port for repairs as has been conducted by USS Somerset [55]. This provides more flexibility for RBN to plan for longer patrols/deployments.

The use of AM across the RBAF workshops would also be beneficial as AM can be used to repair metal parts effectively and produce parts that are no longer in production as in [58] which would provide flexibility to obsolete programs. This capability is not only cost effective; however, it also improved the overall military repair capability and overall military readiness.

In medical aspect, Medical Reception Station (MRS) could utilize AM for their dental services that is tailored specifically to individual's requirement as being done by Jerudong Park Medical Centre

(JPMC). Other than dental, AM could also be used to produce functional prosthetics for military that are injured on the line of duty. The use of AM technology in general would further improve MRS's service, capability and better equip MRS to handle various emergency and trauma cases.

Other than the RBAF context, the use of AM technologies in military research centres within the Ministry of Defence could also enable the rapid prototyping and iteration of military technology research and prototyping such as the design of light weight drones, improved body armour, improved weapons attachments, powered exoskeletons and more.

7.0 CHALLENGES WITH 3D PRINTING

Given the capability and flexibility of the 3D printing have to offer, there is a down side to this technology.

First downside is in the form of quality and consistency. The produced part will typically have a poor surface finish. This requires post-processing such as sanding or polishing which can be time consuming and costly especially in a mass production setting [70]. For consistency, 3D printed part is not produced perfectly and reports suggest that the current 3D printing technology only have the accuracy of about 20-50 microns [71,72], which for a tighter tolerance application such as aviation industries can cause a problem.

Secondly, as mentioned earlier, not all materials can be used as a 3D printer material. Certain manufacturing would require specific material properties and not all properties are available for 3D printing. This means that the material selection is still limited for 3D printing compared to standard manufacturing materials.

Thirdly, most of the manufacturing mentioned are the production of customized or small-scale production of 3D printed parts. At the moment, AM only represent about 0.04% of global manufacturing [73] as the use of AM for mass production is not practical. This primarily due to slow production speed [64,74] and high per-unit cost [75] compared to standard manufacturing methods. Additionally, build volume of the printer requiring larger prints to be divided and assembled separately which is both time and cost consuming for large parts [25].

Fourth, the capital investment for implementing 3D printing technology is high and cost for post-processing need to be taken in to consideration on top of the regular maintenance requirement for the AM system. Additionally, AM materials are often more expensive per unit weight than traditional manufacturing materials and specialized workforce training is required to operate and maintain the equipment [76].

Fifth, with the accessibility of AM technology and the adoption of use in various industries such as aerospace and military, once the 3D files are obtained it could be produced by any suitable 3D printers which is a challenge to protect the integrity of these files especially for military sensitive 3D files. Current mitigation measures did include security features embedded on the file with appropriate encryptions [77] and proper file handling such as the use of private networks for data transmission, digital rights management and blockchain technology [78].

Lastly, disposal of support or failed print needs to be considered as some 3D printing material can be toxic and non-biodegradable [75,79].

8.0 COST-BENEFIT ANALYSIS OF ADDITIVE MANUFACTURING

As additive manufacturing came with its own sets of challenges, in terms of cost-benefit, parts that are requiring customisation would excel as it is cheaper to produce a customised and low-volume production of these parts compared to a mass production where surely traditional manufacturing method would still have an edge with the current technology. This is due to the economy of scale.

An example can be taken from [80] in the production of 50 pieces of simple bracket as in Figure 11. By utilizing traditional manufacturing method, quoted aluminium CNC production would cost approximately $1,300 to $1,990 and injection molding ABS manufacturing would cost about $5,000 and these have a lead time of 9 to14 days. When compared to the utilisation of additive manufacturing technology, production costs are quoted to be as low as $140 (with FDM plastic) to as high as $8,920 (with SLS Steel) depending on material types. For the lead time, production with FDM plastics would took 3 to 8 days whereas SLS Steel would take as long as 21 days.

From this, it could be seen that additive manufacturing can be cheaper and faster (depending on the material) compared to traditional manufacturing with an added flexibility of producing the part in-house. The ability to produce the part in-house can be the most advantageous aspect of additive manufacturing especially on application where returning to base or carrying the machine to produce the part is not feasible i.e. Military deployment, space exploration and etc. The time saved during the production process is also a benefit as time can be costly depending on the situations and the time save is not solely on the production (lead) time of the parts but also the time saved in not requiring the assets to return to base for repairs/parts which will greatly improve military effectiveness during deployment and patrol missions.

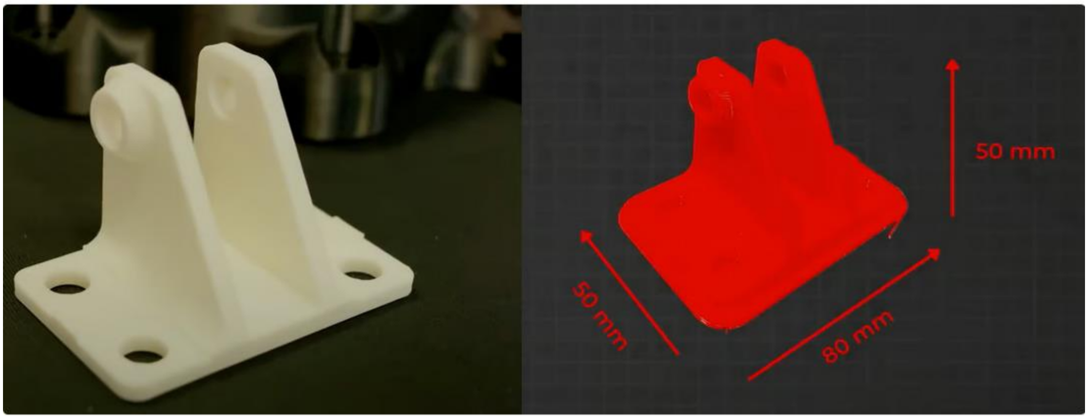

Figure 11. Example of simple bracket that is printed [80].

9.0 FUTURE OUTLOOK FOR ADDITIVE MANUFACTURING

According to market reports, AM market is expected to grow and reach an estimate of $53.84 billion in 2029 which is a CAGR about 25.7% [81]. This is to be expected to cause by factors such as advanced technology integration, material development, partial adoption in the mass production lines and massive adoption on existing industries such as medical to support industrial revolution 5.0 [82].

The use of AI in AM can ensure better quality control of the printed part which reduces the chances of failed print and material waste [83].

Studies are currently being conducted on material to be use for AM and with more material available, it would increase the adoption of AM for different kind of applications. As mentioned earlier, AM has been used in various industries such as aerospace, healthcare, construction and more. These industries have seen a reduction in lead time, lighter printed parts, better compatibility and faster prototyping. With development in large format printing combined with the constant improvement in printing speed and cost effectiveness, AM is becoming more competitive for production scale application especially low-to-medium volume manufacturing which is driving better industry adoption.

In military context, the use of 3D printing enables medical units that is attached on expeditionary unit to reduce its size and weight without compromising capability and agility as medical units would only need to maintain essential medical equipment and print other items on demand on the theatre [84].

10.0 CONCLUSION

AM is a transformative technology with potential to revolutionize the way prototyping, logistics and manufacturing is being done.

The ongoing research on AM material [85] will further improve the list of material selections that will be available which when combined with the current research that are being done for military technologies would see the production of better armour, lighter and stronger drones and many more. The integration of AI in the design and processes of AM and the development of large format will also made AM an attractive option for small to medium volume productions which is applicable for production at the battalion level. With the material efficiency offered by AM compared to traditional subtractive manufacturing, raw material requirement for production would be reduced however it does come at a cost of longer production time which would be acceptable as it does offer customization and enable a small batch production at a reasonable cost compared to traditional subtractive manufacturing which is an added advantage for rapid prototyping. The capability for customization also aligns with the industrial revolution 5.0.

Military adoption of AM technology has been significant with application ranging from military assets manufacturing to operational deployment and exercises. The use of AM in construction of barracks [53] and functional prosthetics [46] is an example where AM technology are also used not only in military contexts however is also applicable in public usage. The widespread of AM technology within and outside of military contexts would benefit the quest for exploration, provide better healthcare services and better readiness during disasters and/or conflict.

The use of AM might not be to replace the traditional manufacturing technology completely; however, a hybrid form of application could be adopted (mix of AM and traditional manufacturing) depending on applicability and AM could also be used as a temporary replacement for parts while waiting for permanent spare to arrive which ensure system uptime and minimizing downtime.

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About the Author

- ***Major (U) Muhd Nurhamizan bin Haji Mawardi***

  He is currently a Combat Ready (CR) Blackhawk S-70i Pilot from 11 Squadron, No.1 Wing, Operations Group, RBAirF with over 800 flying hours. His experience includes being the Exercise Planner for Latihan Bersama (LATMA) Elang Brunesia, focused on Humanitarian Assistance Disaster Relief (HADR) in Brunei Darussalam in 2022 and Pontianak, Indonesia in 2024. He holds a Master of Science (MSc) in Engineering with Business Management from King's College London (2013) and has been serving with the Royal Brunei Armed Forces (RBAF) since 2014.

- ***Lieutenant (U) Mohd Khalid Wassadi Salleh bin Haji Mahmud***

  He is a Limited Combat Ready (LCR) Blackhawk S-70i Pilot from 11 Squadron. He graduated with a Bachelor of Business (Hons) in Business Administration from the University of Brunei Darussalam (UBD) and has been in service with RBAF since 2020, with active involvement in procurement for future capability for 11 Squadron.

- ***Lieutenant (U) Muhd Dzulfadhli bin Bahrin***

  He is a LCR Blackhawk S-70i Pilot from 11 Squadron. He graduated with a Bachelor of Science (Hons) in Psychology with Clinical Psychology from the University of Kent and has been in service with the RBAF since 2020.

- ***Lieutenant (U) Muhd Amirul 'Azmi bin Haji Ali Amzah***

  He is a LCR Blackhawk S-70i Pilot from 11 Squadron. He graduated with a Higher National Diploma (HND) in Mechanical Engineering from University Technology Brunei (UTB) and has been in service with RBAF since 2020.

VIRTUAL REALITY (VR) WINCH TRAINING: COMPLEMENTING LIVE FLYING TO ENHANCE ROYAL BRUNEI AIR FORCE (RBAirF) SEARCH AND RESCUE (SAR) READINESS

Maj (U) Muhd Nurhamizan Haji Mawardi, Lt (U) Mohd Khalid Wassadi Salleh Haji Mahmud, Lt (U) Muhd Dzulfadhli bin Bahrin, Lt (U) Muhd Amirul 'Azmi Haji Ali Amzah
11 Squadron, No. 1 Wing, Operations Group
Royal Brunei Air Force (RBAirF)

ABSTRACT

This paper studies the integration of Virtual Reality (VR) for Search and Rescue (SAR) training for 11 Squadron. Currently, 11 Squadron is responsible for the nation's SAR requirements. SAR operations are very complex and require extensive training to be proficient in the mission. Despite these requirements, SAR training only takes up a small portion of the available training hours allocated each month. In addition, several other challenges have been identified for SAR training, mainly limited flying hours, aircraft serviceability, weather, and the inherent safety risk of live training. Drawing on the 11 Squadron experience with the S-70i Full Flight Simulator (FFS) and relevant international SAR training practices, the paper evaluates the potential of a VR-integrated winch trainer to transfer routine and high-risk training scenarios from live aircraft to a synthetic environment. The findings indicate that VR-based training represents a viable and effective complement to live flying, with the potential to increase training frequency, expand scenario diversity, enhance crew coordination and situational awareness, reduce operational risk, and ease pressure on the S-70i fleet. The paper concludes that VR integration provides a robust and adaptable training platform capable of supporting RBAirF's SAR capability.

Keywords:
Virtual Reality, Winch Training, Search and Rescue, Synthetic Training, Rearcrew, S-70i.

1.0 INTRODUCTION

" As an armed force with a low number of personnel, the Royal Brunei Armed Forces (RBAF) should utilise technological applications as part of the measures to enhance its capabilities."

— His Majesty Sultan Haji Hassanal Bolkiah Mu'izzaddin Waddaulah ibni Al-Marhum Sultan Haji Omar 'Ali Saifuddien Sa'adul Khairi Waddien, Sultan and Yang Di-Pertuan of Brunei Darussalam, Titah at the 60th Anniversary of the RBAF at Taman Sir Muda Haji Omar Ali Saifuddien, Bandar Seri Begawan.

11 Squadron, Royal Brunei Air Force (RBAirF), provides air surveillance of land and maritime borders and the delivery of critical air support across land and maritime defence in Brunei Darussalam [1]. As a multi-role squadron, roles range from special operations, routine troop lifts, underslung load, aerial firefighting, and, recently, the whole national SAR coverage.

Central to this expanded responsibility is the conduct of winching operations, one of the most technically demanding and risk-exposed competencies in SAR [2]. Traditionally, winching training programs have been developed almost exclusively through live flying. While effective, this approach is inherently constrained by limited flying hours, aircraft serviceability, weather, and the elevated safety risks associated with training in high-risk scenarios.

The RBAirF has already recognised the value of synthetic training in mitigating these constraints within its pilot training system. Following the introduction of the Sikorsky S-70i Blackhawk into service, the RBAirF adopted advanced simulation at CAE Brunei Multi-Purpose Training Centre (MPTC) as a core training enabler to support both platform transition and new pilot training [3].

Despite these advances, a disparity remains between pilot and rearcrew training within the SAR domain. While pilots benefit from structured SAR-related simulator training, dedicated synthetic training for rearcrew, particularly in winching operations, remains absent.

This study examines whether a VR-integrated winch trainer can complement live flying by transferring routine and high-risk training scenarios into a controlled synthetic environment. The analysis considers the implications for training frequency, scenario diversity, crew coordination, safety, and operational readiness, in order to assess VR as a scalable and sustainable solution for enhancing SAR capability in the future.

2.0 METHODS

This study employs a mixed-methods approach to assess the feasibility and operational value of integrating VR into winch training for 11 Squadron. Data were derived from 11 Squadron's flying hours over a three-year period, complemented by survey responses collected from both pilots and rearcrew.

To provide broader insight, a series of case studies was also undertaken, examining SAR winch training practices adopted by selected air forces with established and mature SAR capabilities.

Due to the sensitive nature of some of the data used in this study, empirical data are presented as percentages rather than absolute values to preserve operational security (OpSec).

3.0 CHALLENGES

Key limitations include limited flying hours, aircraft and hoist serviceability, weather dependency, and the inherent safety risk of a live-only training. These constraints limit both the frequency and diversity of training scenarios achievable through aircraft-based training alone [4].

Figure 1. Winching Operations Over Water.

Operational Priorities on Limited Flying Hours

Available training hours are constrained by competing demands to sustain operational currency among experienced aircrew while simultaneously supporting the progression of junior pilots and rearcrew. These pressures are further exacerbated by aircraft limitations, as the S-70i aircraft recorded an average 60% serviceability rate in 2025, with a limited number of airframes configured for hoist operations at any given time, reducing live training opportunities, directly influencing the volume of winch training [5].

Operational Risk

Winching operations carry inherent hazards, including cable deterioration, load swing, hoist malfunction, and high workload associated with managing crew and casualties. Live training opportunities to practice emergencies or abnormal scenarios are limited, restricting the ability of rearcrew to acquire and maintain critical competencies in cable management, casualty handling, and emergency response.

Environmental Constraints

Weather minima related to visibility, cloud base, and sea state frequently affect planned training sorties. Even when training proceeds, instructors are required to operate well within the safety margins, limiting realism and intensity of practice.

Brunei Darussalam's equatorial climate further amplifies these constraints. High temperatures, humidity, and frequent convective activity limit stable training windows, often reducing the effective training period of allocated flying hours [6].

Absence of Synthetic Training for Rearcrew

The introduction of the S-70i Full Flight Simulator (FFS) has significantly enhanced pilot training. However, there is no equivalent synthetic training capability for rearcrew training [3]. This creates a proficiency gradient between pilots and rearcrew, especially in winching, creating a need to have an alternative method for crew SAR training.

4.0 POTENTIAL SOLUTION: VR INTEGRATION

This paper proposes the phased introduction of a VR-integrated winch training system as a complementary capability to live flying and the existing S-70i FFS training. The intent is not to replace aircraft-based training, but to address the specific challenges that have been identified by providing a safe training environment for the winch operators and rearcrew.

The proposed system consists of a cabin section mock-up, integrated with immersive visualisation and physical interaction systems. Core components include:

a) **High-Fidelity VR or Augmented-Reality Headsets**
Providing 360° visual environments over land and sea, including ship decks, offshore platforms and confined jungle areas, in line with current SAR winch-training systems used internationally [7].

b) **A Dynamic Hoist Cable with Haptic and Force Feedback**
The ability to replicate load, tension and swing characteristics, similar to new-generation hoist trainers such as Bluedrop's Hoist Mission Training System (HMTS) [8].

c) **An Instructor Console**
A device which enables control of aircraft attitude cues, environmental conditions, emergencies and crew communications, comparable to rearcrew synthetic training systems used by the Irish Air Corps and other SAR operators [9].

These configurations allow winch operators and rearcrew to rehearse full SAR mission segments within a synthetic environment closely matching the cognitive and procedural demands of live operations while remaining independent of aircraft availability and weather.

Additionally, VR sessions can be conducted repeatedly without consuming aircraft hours or airframe life, allowing high-frequency practice for all rearcrew, including ab initios. International operators indicate that synthetic winch training can reduce live-flight time for technical crews by up to 50%, freeing aircraft for operations while maintaining or improving skill levels [10].

VR environments can replicate high-risk conditions, night operations, marginal weather, heavy sea states and complex ship or platform decks that are rarely acceptable for live training. This enables them to experience and rehearse low-frequency, high-consequence situations in depth before facing them on real SAR missions [4].

Winching emergencies such as cable deterioration, cable cut, hoist malfunction, pendant failures and sudden load swing can be practised in VR without endangering aircraft or personnel, including scenarios that cannot be safely or realistically replicated in flight. Engine-related emergencies or flight control malfunctions during hoist operations, currently unsuitable for live training for safety reasons, however, can be rehearsed synthetically, allowing rearcrew to build procedural fluency and decision-making under pressure in a controlled environment [4].

By decoupling a substantial portion of skill acquisition from aircraft availability and weather windows, VR provides a training mechanism that supports higher SAR readiness without a proportional increase in live flying hours, consistent with the long-term sustainability objectives set out in the Defence White Paper (DWP) 2021 [11].

5.0 DISCUSSION

Analysis of flight hour distributions from 2022 to 2024 reveals a constant trend between operational output and SAR rearcrew training requirements within 11 Squadron. On average, approximately 30% of total flying hours are allocated to training activities. However, SAR-specific rearcrew winch training accounts for only approximately 10% of total flying hours annually.

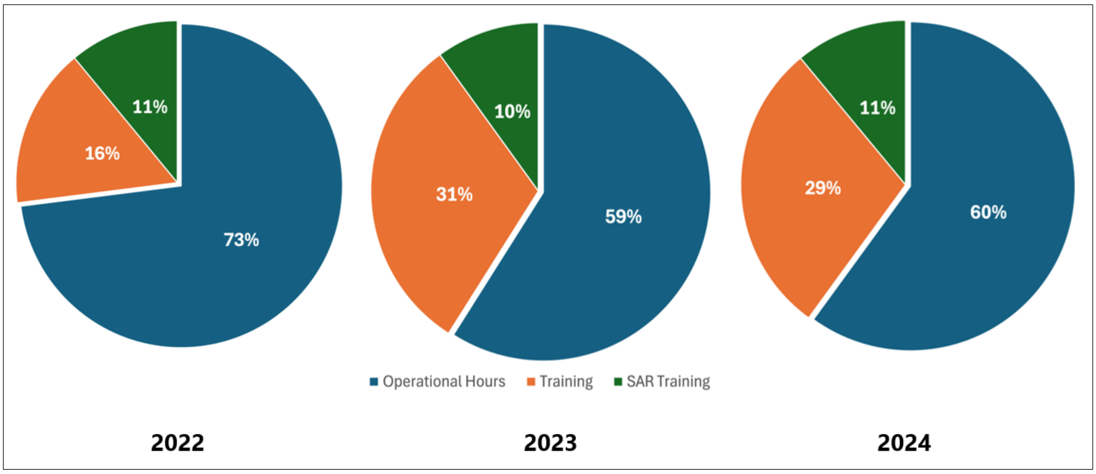

Figure 2. Average Yearly Flight Hour Distribution 2022-2024 [12].

Figure 2 illustrates that in 2022, only 11% of total flight hours were allocated to SAR rearcrew training. Meanwhile, other training activities comprised 16% of the hours, with the majority of 73%

devoted to day-to-day operational missions. The data shows consistency when it comes to SAR training in the year of 2023, showing a consistent range of 10% [12]. The stability of rearcrew SAR training hours, despite rising operational tasking, indicates a limit imposed by finite aircraft availability, serviceability constraints, and competing mission priorities. This supports the need for an alternative method of training.

Furthermore, the findings from an online structured survey completed by 64 personnel, comprising pilots and rearcrew [13]. Several key trends emerged regarding perceived training gaps, constraints in live winch training, and the potential role of VR as a supplementary training. A total of 62% of the participants identified insufficient scenario variety, particularly in night operations and ship operations, which include high sea state, indicating limited exposure to complex operational conditions [13].

Support for the VR integration was generally positive, with 65% of the participants agreeing that simulation or VR could effectively supplement live winch training. Risk management considerations were identified as a major limiting factor, with 75% agreeing that such constraints prevent the practice of realistic scenarios during live training [13].

Although survey responses demonstrated a predominantly positive attitude towards the adoption of VR in training, it only reflects perceived rather than empirically measured effectiveness, and responses may be influenced by familiarity with simulator-based pilot training.

To further support this, interviews conducted specified that the introduction of an FFS for 11 Squadron in Brunei offered a significant advantage and resulted in a marked improvement in training output. All five senior pilots involved in the interview expressed a clear consensus that the introduction of simulator training enables more consistent practices, reinforces procedural knowledge and reduces skill degradation [14].

Captain (U) Azhar Mahathir, Flight Commander Operations (FCO) 11 Squadron, emphasised that the availability of the simulator has fundamentally enhanced training tempo, noting that “It has completely transformed how we view training frequency. We can now integrate simulation seamlessly into our weekly schedules, allowing us to accumulate a volume of training hours that would have been physically unattainable if reliant solely on live flying” [14].

While the local experience demonstrates the tangible benefits of simulator accessibility and utilisation, similar training approaches have also been successfully adopted by air forces with long-established SAR and hoist training programmes.

The Royal Air Force (RAF), known for training quality and professionalism, employs an FFS, integrated with hoist hardware through the Hoist Mission Training System (HMTS) developed by Bluedrop Training and Simulation, in **Figure 3**. This high-fidelity system allows pilots and rearcrew to practice emergency procedures, enhance crew coordination, and conduct rescue scenarios in a controlled environment, minimising operational risk [8].

Figure 3. RAF utilisation of Bluedrop's HMTS for rearcrew.

The RAF's training tools are as follows:

a) **HMTS**
They utilise a state-of-the-art HMTS which enables comprehensive emergency training across various scenarios to enhance rearcrew readiness in handling emergencies. It also works in tandem with their pilot FFS; any input from the pilot will then be reflected on the rearcrew simulator session in real time. The simulator is primarily employed for mission rehearsals, Crew Resource Management (CRM) and skill refinement [8].

b) **Flight Simulator and VR Goggles**
In addition to the HMTS, they utilise a basic flight simulator software with pre-programmed flight profiles, complemented by VR goggles that recreate the cabin environment. This setup enables rehearsals before actual flight missions, optimising aircraft usage by ensuring trainees are proficient in procedures beforehand. [8,15].

Figure 4. The US Army VR simulation system for rear crew winching and air-to-ground role.

Similarly, the United States (US) Army uses the Blackhawk Aircrew Trainer (BAT) for UH-60 crews, providing comprehensive cockpit and cabin simulation. The BAT enables crews to rehearse standard and emergency procedures, including personnel recovery and cargo hoisting, enhancing procedural proficiency and CRM while reducing reliance on live flights. Beyond providing opportunities for deliberate, paced training with breaks for debriefing, simulators serve as a cost-effective measure. The US Army employs various simulator platforms tailored to different roles, including winching and air-to-ground firing training. These platforms allow for repetitive practice and skill refinement in controlled environments, ensuring readiness without the expense and logistical constraints associated with live flight operations [16].

Figure 5. The Republic of Singapore Air Force (RSAF) VR Hoist Simulator.

The RSAF has a VR Hoist Simulator specifically designed to enhance their winching skills, recognising it as one of the most high-risk roles [17]. This simulator offers a controlled environment where the rearcrew can meticulously practice and refine their techniques, mitigating the inherent risks and operational limitations associated with real-world scenarios. By prioritising proficiency in winching operations, they ensure that the rearcrew are thoroughly prepared to execute crucial rescue and operational missions with utmost precision and safety.

While force structure and scale differ, the cognitive, procedural, and risk characteristics of winching operations are platform-agnostic, supporting the relevance of these systems as benchmarks rather than direct templates.

Furthermore, building upon the cost-benefit perspective as portrayed by the US Army, as being cost-effective. The overall operating cost of the VR is significantly less than the cost of live training in the future, despite the required initial start-up cost of the VR of approximately USD 1 million [16]. In comparison to the operating cost of live training, which incurs fuel, maintenance, and hoist serviceability costs. **Figure 6** compares annual of winch specific sorties costs (fuel basis) over 10 years, projecting a rapid Return on Investment (ROI) for VR adoption. It is important to note that fuel costs are only an approximation based on current fuel market price of Jet A-1 based on the average hours of winch specific sorties annually.

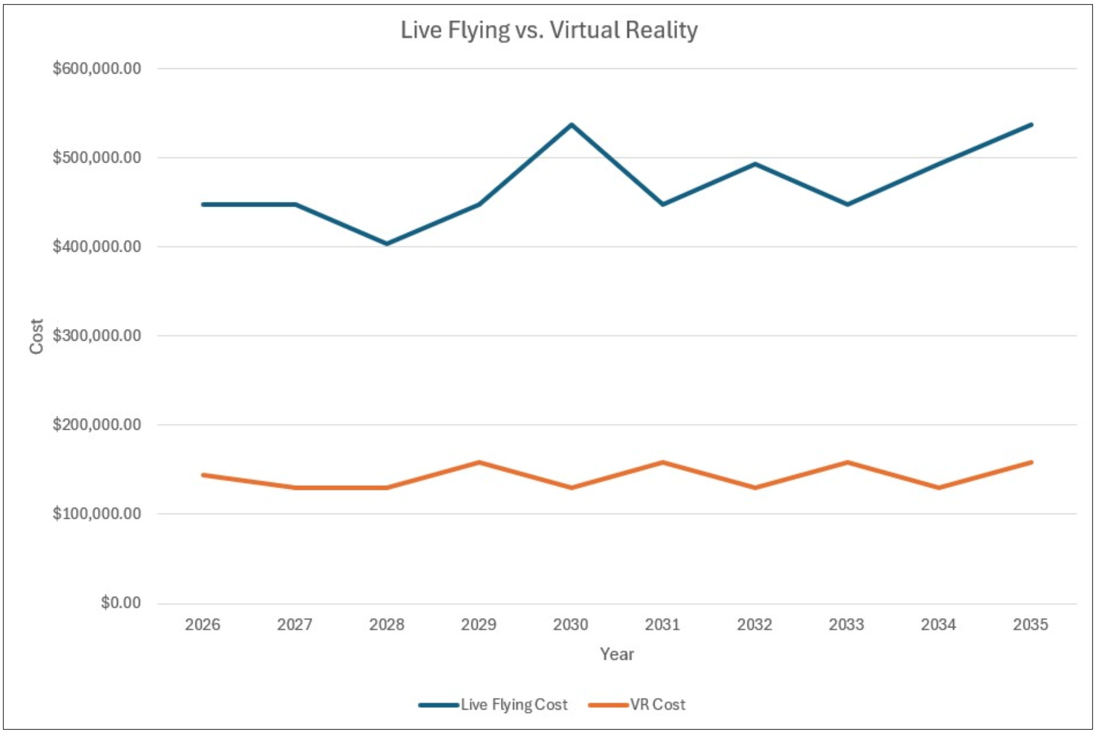

Figure 6. Operating Cost between Live Flying and VR.

Over a 10-year period, the approximation of cost savings would amount to USD 2 million, which is a considerably significant sum in the context of long-term force development and resource optimisation. These savings could be reallocated towards other capability development.

Despite high initial capital investment, VR training presents a financially sustainable solution that complements live training by reducing recurring operating costs while maintaining training continuity and effectiveness. The projected ROI reinforces VR as a prudent and forward-looking training enabler rather than a replacement.

Overall, these examples demonstrate that VR-enabled winch training is increasingly adopted to build rearcrew proficiency through safe, repeatable, standardised practice of high-risk procedures at significantly lower cost and risk. As a benchmark, they support the integration of VR hoist simulation within the RBAirF training continuum to enhance technique, decision-making, and crew coordination while reducing avoidable operational risk and reliance on live sorties.

6.0 CONCLUSION

Modernising winching and SAR rearcrew training through VR is a logical and necessary response to the challenges faced by 11 Squadron, as it assumes the central role in national SAR. In alignment with His Majesty's Titah on leveraging technological applications to enhance capability within a small force structure, the study demonstrates that a VR-integrated winch trainer is both feasible and operationally credible for 11 Squadron.

Building on the established success of high-fidelity S-70i FFS training for pilots, VR offers a means to extend synthetic training benefits to rearcrew, addressing the current imbalance between cockpit-focused simulation and cabin-based SAR tasks.

Therefore, VR-integrated winch training emerges as a viable and strategically aligned enhancement to the RBAirF SAR training system. It provides a credible foundation for sustaining long-term SAR readiness within 11 Squadron and offers a logical starting point and a cost-effective method for broader synthetic training integration in support of future operational requirements across the RBAF.

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About the Author

- ***Captain (U) Fathin ‘Athifah binti Haji Abidin***

She is a Royal Brunei Air Force officer currently serving as Second-in-Command Squadron Commander and Acting Squadron Commander of 41 Squadron, No. 4 Wing, Support Group, Royal Brunei Air Force. She has been serving in the unit since 2020, with progressive appointments across administrative and logistics leadership roles. She began her tenure as an Admin Officer at No. 4 Wing, subsequently serving within the Technical Supply Squadron, later known as 43 Squadron, where she held responsibilities as Officer-In-Charge of the Forward Stores and later as Officer-In-Charge of the Main Stores. These roles provided her with comprehensive operational exposure across supply chain execution, store management, and logistics governance at unit level.

She holds a Master of Science in Management and Finance from Birmingham City University, United Kingdom, underpinning her approach to logistics planning, cost control, and performance optimisation. She has played an active role in the development of the Air Force Domestic Logistics System (ADLS)—an in-house digital platform that centralises inventory data, enhances accountability and traceability, and streamlines logistics workflows by reducing manual processes. Her work contributes directly to improved logistics efficiency, improved decision-making, and strengthened sustainment capability in support of Royal Brunei Air Force operations.

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INNOVATIVE MILITARY CLOTHING AND GEAR FOR THE ROYAL BRUNEI ARMED FORCES (RBAF): ENHANCING HEAT RESILIENCE, SAFETY, AND OPERATIONAL EFFECTIVENESS

Cpt (U) Fathin 'Athifah binti Haji Abidin
41 Squadron, No. 4 Wing, Support Group
Royal Brunei Air Force (RBAirF)

ABSTRACT

An assessment of the requirements of military clothing and personal protective equipment (PPE) within the Royal Brunei Armed Forces (RBAF) has been conducted in this paper to enable enhancements in safety, heat resilience, and operational effectiveness can be done in Brunei's tropical environment. The findings that have been achieved from the study highlighted that there are limitations associated with the current uniforms, which include restricted modularity, limited thermal regulation, inadequate distribution of weight, and insufficient gender-responsive design. A strong potential for improvement has been indicated by the benchmarking against preliminary user feedback and international forces through smart wearable technology, advanced fabrics, and modular load-bearing systems. There is a significant importance of modernising RBAF clothing and gear in reducing injury risks, operational performance can be strengthened, and tri-service capability development can be supported effectively.

Keywords:

Military Personal Protective Equipment; Heat Resilience; Smart Wearable Technology; Modular Load-Bearing Systems; Operational Effectiveness Military Logistics; Logistics Digitalisation; Defence Logistics Systems; Asset Management; Operational Readiness

1.0 INTRODUCTION

The operation of the Royal Brunei Armed Forces (RBAF) is within one of the most demanding tropical environments in Southeast Asia, which is characterised by several factors such as intense heat, high humidity, and frequent heavy rainfall throughout the year. The average daytime temperature mainly ranges between 24°C and 36°C and the humidity levels remain above 80% consistently. There are extreme environmental conditions upon which the soldiers are routinely exposed during the operational deployments, training, humanitarian assistance, maritime activities, and disaster relief operations. There is a significant influence of these climatic conditions on the decision-making ability, physical endurance, and operational tempo, especially during the operation under heavy equipment loads and prolonged missions.

With the consistent strategic transformation agenda of RBAF, personal protective equipment (PPE) and modernisation of clothing systems have become a critical requirement. Moreover, the transformation agenda is also in alignment with the capability development, national defence priorities, and ongoing digitalisation initiatives within the Ministry of Defence. There is a rising demand for tri-service collaboration, interoperability, and integration of new technologies with the evolutions of the nature of military operations. This enhances the survivability, situational awareness, and operational agility of the military system. In parallel, there is a rising adoption of smart wearables, advanced textiles, gender-responsive equipment, and modular gear systems by the global defence forces. Hence, the requirement for the RBAF to review and upgrade its PPE and modern clothing is being reinforced by the global trend so that the RBAF can remain technologically competent and operationally resilient.

However, although several improvements have been made, there are several limitations that are being faced by the current RBAF uniforms and protective gear that affect optimal performance in the tropical environment. There are several aspects which are included in it such as limited moisture-wicking capability, insufficient heat resilience in fabric technology, gaps in comfort and fit for female personnel, and suboptimal weight distribution for load-bearing equipment. Moreover, limited integration capacity with emerging smart-technology components is also present in the current systems, which includes environmental monitoring, biometric sensors, and real-time communication support. There is a significant influence of these limitations, which contributes to reduced ergonomic efficiency, increased fatigue, enhanced risk of heat-related injuries, and reduced mission endurance. Hence, a proper management of these limitations needs to be done by which these challenges can be minimised effectively.

The main aim of this paper is to evaluate the personal protective equipment and innovative military clothing, which must be in alignment with the operational requirements and modernisation goals of RBAF. This includes assessment of the modular load-bearing systems, advanced materials designed for heat management, smart wearable technologies, and improved flame-resistant protection. Moreover, potential ways of collaborative development and phased implementation are also to be identified in this paper through industry partnerships, defence science research, and assessment of user feedback within the tri-service environment.

There is a significance of this study as by conducting it properly, enhancement of safety, operational performance, and resilience of RBAF personnel can be done by improving survivability, reducing physiological stress, and increasing the readiness of the mission. For the Royal Brunei Land Forces, Royal Brunei Navy, and Royal Brunei Air Force, the future-ready force can be achieved by enabling modernised clothing and gear by which proper and effective response to the identified challenges can be provided appropriately.

2.0 LITERATURE REVIEW

The development of modern military clothing and personal protective equipment (PPE) has been evolving substantially during the last 20 years because of the development of textile science, ergonomics, and technology in the battlefield. The worldwide defence forces are becoming more aware of the fact that uniforms and protective clothing are not just a standard issue garment again, but an essential part of the survivability, physical performance, and mission effectiveness of the soldier [1]. It has been pointed out in research that operational clothing should fulfil several requirements such as heat management, durability, mobility, ballistic protection and compatibility with load-bearing and communications systems to give the clothing the best functionality in the course of a military operation. Such needs are increased in tropical areas like Southeast Asia where the humidity and the exposure to heat pose significant physiological problems to military personnel.

2.1 | Advanced Fabrics for Heat Resilience and Moisture Management

There are a lot of recent studies that have been incorporated which highlights the significance of high-performance fabrics that have active mechanisms of controlling body temperature and promote thermal comfort under the extreme weather conditions. The adoption of the moisture-wicking and quick-drying textile, mesh ventilation systems has been implemented in modern armies like the Singapore Armed Forces (SAF) and the Australian Defence Force (ADF) to minimize the heat build-up and boost the evaporation cooling of the forces [2]. Research indicates that thermal stress and heat injuries have a notable adverse effect on cognitive processing, reaction time, and decision-making ability, which affect the mission outcomes and safety [3]. New textile technologies such as phase-change materials (PCM), anti-microbial treatments, and UV-resistant finishes were also introduced to stop heat accumulation and bacteria growth under prolonged field conditions [4]. In tropical forces in the jungle environment, this type of material helps in endurance and minimizes chances of operational downtime.

2.2 | Sensor Integration and Smart Wearable Systems

Innovations in the defence technology of late have presented wearable electronic systems by which real-time information on the health, hydration, fatigue and environmental statuses of the soldiers are being offered. There are several experiments that have been done by the United States Army and British Armed Forces concerning using the integrated physiological sensors as part of uniforms and body armour to enhance situational awareness and command decision support [5]. These systems allow heat exhaustion, dehydration and over-exertion to be detected early on thus lowering the number of injuries that could be prevented. The preferences of the future studies are on the textile-based antennas, power-distribution, and connectivity of heads-up displays to allow flow of communication without adding weight to the load or limiting the mobility of people. Furthermore, there are still some issues that are associated with battery life, environmentally sustainability, and cyber-security protection needs.

2.3 | Modular Load-Bearing Equipment and Ergonomics Performance

Research has indicated that heavy burdens on the soldiers are some of the leading causes of musculoskeletal injuries, fatigue, low mobility and impaired operational capacity [6]. Modern load systems like the MOLLE (Modular Lightweight Load-carrying Equipment) system used by the NATO troops and the Canadian Army Integrated Soldier System illustrate how modularity can be useful to redistribute weight and provide mission-focused designs. Modular gear systems enable the personnel to change the equipment according to the terrain, task or level of threat, which reduces unnecessary strain [7]. Enhancement of load handling is of much concern especially in maritime and aero missions where emergency exits and speed of movement demand a high degree of agility.

2.4 | Gender Responsive Design of Uniforms and PPE

The initiative of integrating women into frontline and specialist positions in most of the militaries has been a boost to the need to develop PPEs and uniforms that are designed to meet the female anthropometric sizes. It is found that improperly fitting armour and clothing deteriorate motion, heighten risks of injury, and minimise the effectiveness of operations [8]. The UK MoD and the US Marine Corps have also launched female-fitting body armour and adaptable uniforms so that performance and comfort are enhanced. The more women join RBAF services, the more gender-responsive equipment should be taken into account to achieve a balanced level of safety and the capability criteria.

2.5 | Relevance to the Royal Brunei Armed Forces

Within the RBAF, the current uniforms and PPE have experienced a series of minor enhancements, by which optimised heat experiences are not being provided, a modular load-management system, smart-technology, and fit-inclusivity [9]. Considering the demanding operational environment of the tri-service missions with high temperature and a variety of mission needs, the ability to integrate international best-practice and research lessons in facilitating the impetus of defence modernisation and digital transformation is essential.

3.0 METHODS

In this study, the comparative benchmarking and user-need analysis methodology is used to analyse the opportunities of the improvement of military uniforms and personal protective equipment (PPE) of the Royal Brunei Armed Forces (RBAF). The methodology entails a combination of secondary research, analysis of best practices across the world, and insights on frontline users to determine the gaps of capabilities and needs that may be applicable in the operational environment of the RBAF.

3.1 | Comparative Benchmarking

The benchmarking analysis has been done based on the comparison with the chosen global military forces which have made modernisation efforts in combat uniform and defence equipment [10]. The choice of reference forces was based on the close resemblance of the operating environments of the tropics, technological development, and the applicability to the interoperability and training collaboration. These were Singapore Armed Forces (SAF), Malaysian Armed Forces (MAF), Australian Defence Force (ADF), United States Army and the United Kingdom Ministry of Defence. Research articles, defence publications, and case studies, which were publicly available, were reviewed in order to compare progress in fabric performance, modular load-bearing systems, ballistic protection, and wearable sensor integration. This benchmarking procedure aids in the identification of known innovations which can be adapted by the RBAF, and the organisational size and climate as well as profile of missions [12].'

3.2 | User Needs Assessment

The military clothing and gear mostly are used by operational personnel so it is important to understand their lived experience to determine the efficiency of existing systems. A conceptual survey design that resembles the one used in the Air Force Domestic Logistics System (ADLS) study was viewed as a proper tool to determine the perceptions and needs of a soldier with heat performance, comfort, mobility, durability, and gender fit of the existing uniforms and PPE. Even though the results of surveys are at their early exploratory phase, user feedback has been identified as of paramount importance in setting up feasible priorities and confirmation of research assumptions [11]. The inputs were divided into performance constraints, ergonomics, safety concerns and future improvement expectations.

3.3 | Evaluation Criteria

A multi-criteria evaluation framework that includes five major dimensions, namely, was constructed to evaluate the potential innovations:

1. Climate suitability, such as heat resistant, breathable, moisture treatment and temperature control;
2. Safety and protection performance, which includes ballistic and flame resistance, impact absorption, and shock mitigation;
3. Integration capability, which is concerned with modular gear integration, sensor integration, and load-distribution systems;
4. Human factors and inclusivity, which evaluates the female-specific sizing, ergonomic fit, and mobility;
5. Cost and feasibility, sourcing, maintenance, scalability and possibility of implementation in phases.

3.4 | Data Analysis

The collection of data has been done through benchmarking and user feedback and its qualitative analysis has been done as compared with the evaluation framework in order to come up with capability gaps and areas of priority improvement. Results also form the basis of the Results and Discussion sections that describe the proposed innovations to be made in RBAF clothing and PPE modernisation in accordance with the strategic transformation goals.

4.0 RESULTS

The comparative benchmarking and preliminary user response indicate that both the main capability gaps in the existing RBAF military clothing and personal protective gears (PPE), and the focus areas that require an improvement. A significant revelation has been found from the results that the current uniforms and equipment are very simple in nature and are not highly climate adaptive and ergonomically efficient with the requirement of functioning in long term under the Brunei climate conditions. Thermal control, moisture and ventilation were noted to be limited regularly and were cited as factors that caused discomfort and heat stress, especially when engaged in long field exercises as well as jungle operations. Problems with weight distribution during the carrying of load-bearing equipment were also reported by the users, which made the carrying of such equipment more fatigued and slowed.

Moreover, the review also found formalised limited integration of the emerging smart technologies, including; physiological monitoring sensors, digital connectivity elements, or condition-based performance feedback system, which are becoming standard in the event of modern defence forces. Lack of modularity in existing gear is a limitation to mission-specific configuration, and the increase in female personnel has indicated the potential to design uniforms specifically to meet the needs of each gender, allowing better fit, safety, and efficiency.

Table 1. Identified Capability Gaps and Innovation Priorities.

Area Identified	Current Issue	Required Improvement Priority
Heat resilience & thermal comfort	Poor ventilation and heat stress	Integrated cooling technologies, moisture-wicking textiles, and advanced breathable fabrics.
Smart technology integration	No support of digital connectivity or sensor	Communication compatibility and wearable monitoring systems
Load-bearing ergonomics	Uneven distribution of weight	Improved harnessing, balance support, and modular systems
Protection and durability	Standard ballistic rating	Enhanced flame, cut and impact resistance
Gender responsive design	Limited female fit and sizing	Alignment of ergonomic design to body dimensions

Hence, the requirement of modernisation of PPE and RBAF clothing is being supported by the results, with an emphasis on human-factor engineering, advanced materials, technology-integration, and modularity. Hence, by these findings, the foundation for strategic implementation pathways have been established.

5.0 DISCUSSION

It shows that there is a definite need to modernise military clothing and personal protective gear at the Royal Brunei Armed Forces to improve operational performance, safety, and resilience in tri-service settings. The identified capability gaps, especially those associated with heat resiliency, ergonomic load distribution, gender inclusivity, and the lack of technology integration, represent the issues that militaries. These have to operate in hot and humid climates that are being faced usually. The heat stress and the physical fatigue are also important operational risks, which have impact on endurance, cognitive performance as well as mission readiness [13]. Thus, the use of high-tech textile technologies, including moisture-wicking fibres, phase-change thermal regulation substances, and antimicrobial treatment, is a viable opportunity to minimise physiological load during extended field assignments.

The benchmarking review reveals that a significant shift among the defence forces has been towards modular load bearing systems and smart wearable monitoring systems to enhance flexibility, security and responsiveness in the command. By incorporating the innovations into RBAF, there would be a possibility to organise the equipment more efficiently, increase mobility, and help to identify heat-related injuries or over-exertion ones in the early stages. Similarly, uniform and armour design would remain gender responsive to provide fair protection and comfort and cover the increasing number of female personnel in specialised duties [14].

Modernisation efforts as they provide have significant advantages, but implementation can be through a gradual adoption process because of financial and procurement factors. Collaboration with manufacturers of the defence industry, support of DSTG research, and formal user testing will be essential to make sure that it is suitable for missions in Brunei and its tropical climate. Moreover, the transition to innovative clothing and PPE solutions correlates with the strategic goals of modernisation and digitalisation of the RBAF, which increases preparedness and makes the work more efficient in the field of land, maritime, and air operations.

6.0 CONCLUSION AND RECOMMENDATION

Conclusively, it can be said that there is a significant importance of modernising the military apparel and personal protection gear of the Royal Brunei Armed Forces to make it suitable to the contemporary operation needs and ecological conditions. The existing uniforms and equipment, although practical, are not maximally heat-resistant, ergonomic, gender-neutral, or compatible with the future smart systems. There are several impacts of these constraints such as less mobility, fatigue, and augment heat-related injuries, by which mission endurance and security throughout tri-service counterintelligence are being influenced. The breakthrough of clothing trends and PPE with the help of innovative materials, adjustable load-carrying mechanisms, more protective fabrics, and wearable technology will go a long way in enhancing physical performance, survivability and operational preparedness.

There are several recommendations that can be provided by which the effective implementation of the modernisation system can be done. This can be started with the phased and trial-based procurement strategy is to be considered, and it should start with the testing of prototypes in cooperation with the Army, Navy, and Air Force end users. Second, it should form partnerships with the defence research organisations, experts in the field of textile technology and manufacturers in the industry to facilitate quicker innovation [15]. Thirdly, the ergonomic fit and gender-responsive sizing should be on top of the list to make sure that everyone is compatible. Last but not least, the systematic review and user-feedback systems must be integrated to constantly improve the performance results. A forward-looking investment in new clothes and equipment is thus critical to assisting Force transformation at RBAF and being able to have a resilient and future-ready military force.

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About the Author

- ***Lieutenant Colonel (U) Malcolm Craig***

He is the Head of Aviation Safety, RBAirF joining the RBAF following 4 years employed as an Aircraft Accident Investigator and UK Defence's only Crash Site Manager. Post-Graduate trained in Air Accident Investigation he has investigated several fatal and not fatal catastrophic aircraft losses including the loss, search and salvage of an F35 from the carrier HMS Queen Elizabeth. Additionally, he is qualified in Aircraft Post-Crash Management [including embarked air operations], Disaster Victim Identification, Maritime Accident Investigation, Human Factors Training Facilitation and Forensic Photography.

- ***Major (U) Azhar @ Reamy bin Hj Jumat***

Major (U) Azhar @ Reamy bin Hj Jumat, academically trained in Business and Finance [Banking], has served since 2008 from OCS Intake 1. He has flown the Bell 212 and later the Blackhawk S70i, accumulating approximately 1,700 flying hours, and presently holds the appointment of SO2 Aviation Safety, RBAirF.

- ***Captain (U) Norasiah bin Hussin***

She serves as the SO3 Aviation Safety, RBAirF and is the second female pilot in the RBAirF. A proficient and dedicated aviator, she has accumulated approximately 1,000 flying hours and continues to contribute significantly to the advancement of aviation safety within the organisation.

HUMAN FACTORS AND ERGONOMICS IN ROYAL BRUNEI AIR FORCE (RBAirF)

Lt Col (U) Malcolm Craig, Maj (U) Reamy bin Hj Jumat, Cpt (U) Norasiah bin Hussin
Aviation Safety
Royal Brunei Air Force (RBAirF)

ABSTRACT

This article examines Human Factors and Ergonomics (HFE) in relation to two key RBAirF platforms: The S-70i Blackhawk and the C295MW. It highlights cockpit design, environmental stressors, long-duration mission effects, and the importance of integrating HFE into future aircraft procurement. Brunei's tropical climate presents unique physiological challenges that directly affect aircrew endurance, cognitive performance, and operational decision-making, underscoring the need for RBAirF to continually adapt procedures, training, and platform requirements to ensure mission safety and effectiveness.

Keywords:
Human factors, aviation safety, performance.

1.0 LITERATURE REVIEW

A substantial body of Human Factors and Ergonomics research provides the foundation for understanding how aircrew perform in demanding operational environments. Studies by NASA's Human Factors Division show that heat stress impairs cognitive processing, slows reaction time, and reduces fine-motor accuracy, factors that directly affect aircraft handling in non-air-conditioned platforms such as the S-70i Blackhawk [**1**]. Research by Wickens and the European Union Aviation Safety Agency [EASA] further emphasises the value of intuitive cockpit layout, appropriate anthropometric design, and well-structured displays in reducing pilot workload and preventing task saturation [**2**,**3**]. Additionally, long-duration flight studies outlined in broader ergonomic literature demonstrate that fatigue accumulates due to prolonged sitting, sustained vigilance, and the combined effects of vibration and noise exposure, influencing mission performance in aircraft such as the C295MW [4]. Collectively, findings as such can be used as references to understand how environmental stressors and ergonomic limitations can significantly affect operational effectiveness and safety within the RBAirF. It underscores the need for platform design and operational procedures that fully consider the physiological and cognitive demands placed on aircrew. These research insights provide a basis for examining how human factors manifest within current RBAirF platforms, beginning with cockpit ergonomic design.

Building on these research findings, military-focused ergonomic literature further highlights the importance of effective Human-System Integration [HSI] in aircraft procurement. Studies consistently show that poor alignment between human capability and system design contributes to higher error rates, slower decision-making cycles, and an increased risk of injury during complex operations [4,5]. These outcomes reinforce broader global aviation safety trends that emphasise designing systems around human limitations rather than expecting individuals to compensate for poorly matched equipment. For the RBAirF, this evidence underscores the operational necessity of ensuring that future platforms are selected and configured with HFE and HSI principles as core criteria rather than secondary considerations. Integrating these principles directly supports safer mission execution, reduces human error potential, and enhances long-term aircrew performance and well-being. This foundation sets the stage for examining how ergonomic principles are applied in current RBAirF platforms, beginning with cockpit design and physical interface considerations.

2.0 INTRODUCTION

Aviation safety is deeply influenced by the human element. As such aircraft systems, mission demands and environmental conditions must be aligned with human capabilities and limitations. To optimise the role of people in complex working environments involves all aspects of human performance and behaviour such as Information Processing, Situational Awareness and Decision Making, Fatigue, Stress and Performance, Group Dynamics [Leadership and Followship] as well as communication.

Conceptually, Human Factors can be defined as the interaction between:

1. People and People
2. People and the Machine
3. People and Procedures
4. People and the Environment

2.1 | SHELL Model

The conceptual model can be represented by the SHEL[L] model, first developed by Edwards in 1972 and later adapted by Hawkins, and which uses blocks to represent the different components of Human Factors. The blocks of the model are:

1. **S**oftware - The interface between people and software; the procedures, and written documents, which are part of the Standard Operating Procedures.

2. **H**ardware – The interface between people and hardware; equipment, controls, displays and functional systems.
3. **E**nvironment – The interface between people and the environment; the situation within which the people must operate including the natural environment.
4. **L**iveware – The interface between people and other people; process of working within teams.

This conceptual model places an additional Liveware in the middle to represent the interface between the other 4 blocks of the model. The practical value of the SHEL[L] model is supported by quantitative analyses of real-world accidents. A study on Indonesian civil aviation accidents and serious incidents from 2015–2019 used the SHELL framework to code causal factors and found that 64% of occurrences were primarily driven by Liveware–Liveware mismatches, most often associated with inadequate management supervision (74%), lack of rules (22%) or poor coordination (4%) [8]. Similar systems-based approaches, such as the Human Factors Analysis and Classification System (HFACS), consistently show that approximately 70–80% of civil and military aviation accidents involve human error rather than purely technical failure [9–11]. Broader reviews have likewise reported that more than half of aircraft accidents investigated and over 60% of recorded mishaps contain operations-related human causal factors [12]. In parallel, fatigue-focused studies within air forces and airline operations demonstrate that up to 94% of aircrew report performance-degrading fatigue symptoms, with associated reductions in situational awareness and increased minor errors [13,14]. Collectively, these findings indicate that the majority of aviation risk arises at the interfaces described by the SHEL[L] model, reinforcing its relevance as a structured tool for analysing RBAirF occurrences, prioritising safety interventions and informing future platform acquisition decisions.

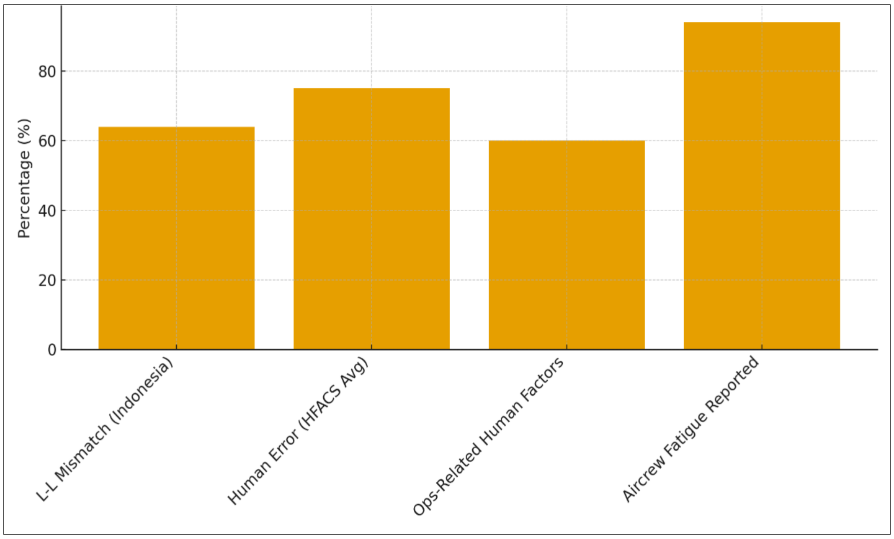

Figure 1. Human Factors Impact.

Brunei's hot and humid climate presents unique stress factors that directly affect aircrew physical, physiological, and psychological operational performance. Elevated cockpit temperatures in non-air-conditioned platforms such as the Blackhawk S-70i exacerbate heat stress, which has been shown to impair cognitive processing, slow reaction time, and degrade fine-motor accuracy [2]. These environmental conditions also intensify fatigue accumulation, consistent with studies reporting that up to 94% of military and airline aircrew experience performance-degrading fatigue symptoms during prolonged operations [13,14]. Furthermore, mismatches between environmental demands and human-system interfaces, captured within the SHEL[L] model, mirror findings that 64% of aviation incidents in the Indonesian SHELL study were driven by Liveware–Environment and Liveware–Liveware mismatches [8]. Understanding how Brunei's operational environment amplifies human-factor vulnerabilities is therefore essential in order to strengthen and elevate awareness of flight safety in RBAirF, by tailoring training and aligning procedures, and thus guide future platform acquisition decisions.

3.0 ERGONOMIC DESIGN IN MODERN RBAirF PLATFORMS

At the centre of Human Factors is the person, the most critical and most adaptable component within the aviation system. Human performance varies due to physical, physiological, and cognitive limitations, many of which are predictable and must be considered in the design and operation of any aircraft. For this reason, all other elements of the system must be structured in a way that does not impose unnecessary stress on the aircrew, particularly in demanding environments such as Brunei. Understanding the human operator requires consideration of several key characteristics.

3.1 | Physical size and shape

Body measurements and movement capability vary significantly across age, ethnic, and gender groups. Cockpit design must therefore accommodate a wide anthropometric range to ensure safe control access, posture, and visibility.

3.2 | Physical needs

Human requirements for hydration, nutrition, and oxygen directly influence endurance and operational effectiveness, especially during long-duration missions.

3.3 | Input characteristics

Aircrew rely on visual, auditory, and tactile sensory systems to interpret the environment and operate the aircraft. These senses can degrade under heat, vibration, humidity, and noise — conditions frequently encountered during RBAirF operations.

3.4 | Information processing

Short-term and long-term memory, workload capacity, and susceptibility to physical or psychological stress affect situational awareness. Reduced situational awareness increases the likelihood of poor decisions during critical phases of flight.

3.5 | Environmental tolerances

Human performance is shaped by temperature, pressure, humidity, noise, light levels, and spatial constraints. Extreme or sustained environmental stressors can impair judgement, coordination, and overall well-being.

These characteristics demonstrate why ergonomic design is essential in mitigating human limitations and optimising operational performance. Modern cockpit ergonomics aim to reduce workload, support natural human posture, and minimise physical strain. In both the S-70i and the C295MW, seating systems are designed to maintain spinal stability during prolonged operations; control placement allows pilots to interact with the aircraft without excessive reach or effort; and instrument displays are arranged to support rapid information scanning. Wide visibility angles further enhance situational awareness during demanding tasks such as hover manoeuvres, approaches, and Night Vision Goggles (NVG) operations.

Together, these elements show that integrating ergonomic principles into platform design is not optional but fundamental, particularly for the RBAirF, whose aircraft must support diverse aircrew operating in Brunei’s challenging environmental conditions.

4.0 HEAT STRESS IN THE S-70i BLACKHAWK

The RBAirF variant of the S-70i does not include an air-conditioning system, and in Brunei’s tropical climate this presents a significant operational challenge that directly interacts with the human-factor limitations outlined earlier. Cockpit temperatures rise rapidly during hover, ground operations, and SAR tasks, elevating core body temperature and accelerating dehydration. As heat builds, cognitive clarity declines and reaction times slow, reducing the fine-motor accuracy required for precision tasks such as confined-area landings and hoist operations. These effects are consistent with NASA’s heat-stress research, which demonstrates that even moderate temperature increases impair decision-making and motor coordination [2]. When viewed through the SHEL[L] model, this represents a clear Liveware–Environment mismatch, one that amplifies human vulnerability and increases operational risk. This reinforces the broader argument of the journal: that environmental stresses in Brunei must be central considerations in cockpit design, platform selection, and future aircraft procurement, particularly for high-workload helicopters such as the S-70i.

Figure 2. The S-70i Blackhawk operating in tropical conditions.

5.0 LONG-DURATION FLIGHT IMPACTS [C295MW]

The C295MW routinely conducts long-duration missions, including maritime patrol, transport flights, and extended surveillance operations, making it a platform where the cumulative effects of Human Factors are especially evident. Even with an environmental control system, aircrew are subjected to prolonged sitting, sustained vigilance requirements, and extended periods of display monitoring. Over time, these conditions lead to musculoskeletal discomfort, cognitive fatigue, reduced attention span, and visual strain, factors highlighted in long-duration flight research and fatigue-survey findings, where up to 94% of aircrew reported performance-degrading fatigue symptoms [13,14]. These effects become most pronounced during the final phases of flight, when workload intensifies and decision-making demands peak, creating a classic Liveware–Environment and Liveware–Hardware interface challenge within the SHEL[L] model. This reinforces the broader argument that fatigue management, ergonomic seating design, and workload distribution are essential considerations for RBAirF operations, particularly as long-duration missions continue to form a core component of the C295MW's operational profile.

6.0 CONSOLIDATED HUMAN FACTORS INSIGHTS

International studies in Human Factors reinforce the key themes emerging from the earlier analysis of RBAirF operations. Heat stress highlighted in the S-70i context remains one of the most significant threats to cognitive performance, particularly in platforms without environmental cooling, where rising cockpit temperatures directly impair decision-making and fine-motor accuracy [2]. Likewise, findings from long-duration flight research align with challenges observed in the C295MW, showing that fatigue accumulates rapidly during sustained vigilance and prolonged sitting, with up to 94% of aircrew reporting performance-degrading fatigue symptoms [13,14]. Effective cockpit ergonomics, therefore, become essential in reducing human error by minimising physical strain, improving reach and visibility, and supporting natural workload flow, core aspects of the Liveware–Hardware interface. At the same time, the environmental and physiological stresses described earlier emphasise the importance of hydration management, airflow optimisation, rest planning, and environmental control across all mission types. Taken together, these considerations affirm that the Human Factors challenges faced by the RBAirF are consistent with global research trends and must be central to future operational planning, training, and platform acquisition decisions.

7.0 PROCUREMENT IMPLICATIONS FOR RBAirF

The evidence presented throughout this article demonstrates that Human Factors and Ergonomics must be positioned at the centre of future aircraft acquisition decisions for the RBAirF. The heat-stress challenges identified in the S-70i, the cumulative fatigue effects observed in long-duration C295MW missions, and the global research showing that up to 70–80% of aviation accidents stem from human-system mismatches collectively highlight the operational cost of overlooking human limitations [8–11]. For tropical environments such as Brunei, effective cooling systems and cockpit airflow are essential to preserving aircrew physiology and maintaining cognitive performance. Seating design, posture support, and anthropometric accommodation must reflect the diverse physical profiles of RBAirF personnel, while cockpit layout, automation, and workload distribution should minimise task saturation and strengthen decision-making under pressure. Additionally, cabin configuration should support mission-crew coordination, and vibration-dampening and fatigue-reduction technologies are necessary to mitigate the long-term effects of sustained operations. Platforms that prioritise human performance do not merely enhance comfort, they directly improve operational safety, mission effectiveness, and long-term sustainability for the RBAirF.

8.0 CONCLUSION

The Blackhawk S-70i and C295MW remain vital and highly in-demand platforms within the RBAirF fleet. However, the analysis presented in this article demonstrates that their effectiveness is inseparable from the Human Factors and Ergonomics considerations that shape aircrew performance. Heat stress in the non-air-conditioned S-70i, cumulative fatigue during long-duration C295MW missions, and the wider body of international research showing that the majority of aviation risk arises from human-system mismatches collectively highlight the need to prioritise the human element in all aspects of aviation safety. When interpreted through the SHEL[L] and HFACS frameworks, these challenges underscore the importance of aligning hardware, procedures, environmental conditions, and organisational practices with human capabilities and limitations. For the RBAirF, this means that future aircraft procurement, cockpit design, and mission planning must adopt HFE principles as foundational criteria rather than optional enhancements. Ensuring adequate thermal management, ergonomic seating, anthropometric accommodation, intuitive displays, workload-sensitive automation, and fatigue-mitigating technologies will directly strengthen operational safety and mission effectiveness. Ultimately, platforms that are designed around the human operator not only reduce error and enhance performance but also safeguard the long-term health, resilience, and readiness of RBAirF aircrew, ensuring that the Force remains capable, adaptive, and safe in Brunei's demanding operating environment.

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