



THE IMPACT OF CLIMATE CHANGE ON THE RELIABILITY AND RESILIENCE OF DEFENSE ELECTRONIC SYSTEMS

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ABSTRACT

As global climate patterns shift toward more frequent and intense extremes, the operational reliability of defense electronic systems—the core of modern military capability—faces unprecedented environmental stress. This study investigates the correlation between climate change variables and the degradation of Army electronic hardware through a systematic literature review. Analysis of data from military standards (MIL-STD-810H) and strategic climate projections reveals that rising mean temperatures, persistent humidity, and increased atmospheric salinity significantly accelerate failure modes such as thermal aging, electrochemical corrosion, and dendritic growth. The findings indicate that traditional engineering safety margins, established using static historical data, are increasingly insufficient to maintain Mean Time Between Failures (MTBF) in tropical and volatile theaters. The paper concludes that a paradigm shift in defense procurement is required, recommending the adoption of wide-bandgap (WBG) semiconductors, AI-driven Prognostics and Health Management (PHM), and revised ruggedization protocols to ensure combat readiness in an era of climate volatility.

Kata kunci: *Climate Change, Defense Electronics, Reliability Engineering, Military Standards, Thermal Degradation, Strategic Resilience.*

INTRODUCTION

Modern defense electronic systems serve as the backbone of military power, demanding absolute reliability across all operational theaters. However, current defense design paradigms face a localized and unpredictable challenge: global climate change. Rising mean temperatures and extreme weather anomalies are no longer merely environmental concerns but represent an asymmetric threat that directly degrades the integrity of semiconductor materials and control systems within military hardware (United States Department of Defense, 2021).

The reliability of Army electronic assets, such as tactical radios and combat vehicle navigation systems, is heavily contingent upon environmental thermal stability. Based on the Arrhenius law, the failure rate of electronic components increases exponentially with operational temperature; specifically, every 10°C rise in temperature can reduce a component's lifespan by 50% (Pecht, 2009). This condition is exacerbated by heatwave phenomena that now frequently exceed traditional military design limits, triggering premature failures in both active and passive heat dissipation systems.

Beyond thermal factors, shifting climate patterns are driving extreme

humidity and air salinity in regions previously considered stable. High humidity acts as a catalyst for electrochemical corrosion and the formation of tin whiskers on printed circuit boards (PCBs), leading to catastrophic short circuits (Klyatis, 2018). For land forces operating in tropical and coastal corridors, these dynamics increase the frequency of damage to sensitive electronic modules before they reach scheduled maintenance cycles, directly undermining combat operational readiness.

While environmental testing standards such as MIL-STD-810H have been updated, a significant gap remains between laboratory simulations and the increasingly volatile reality of the field. Most military equipment currently in service was designed based on static climate data from previous decades, rendering it incompatible with future projections of weather extremities (Intergovernmental Panel on Climate Change [IPCC], 2023). Failure to mitigate the impact of climate change on defense technology could result in massive budgetary inefficiencies due to unplanned and skyrocketing repair and maintenance costs.

This study aims to critically analyze the influence of climate change on the resilience of defense electronic systems through a systematic literature review. By evaluating material degradation data and the latest climate projections, this research maps the technical risks faced by Army electronic devices and formulates material adaptation strategies. The findings of this study are expected to provide a foundation for defense policymakers to update procurement and maintenance standards in the era of climate crisis.

RESEARCH METHODOLOGY

This study employs a **Systematic Literature Review (SLR)** method with a

qualitative-descriptive approach. The primary focus is to synthesize data from various credible sources to map climate change risks specifically affecting Army electronic hardware.

Literature Search Strategy

Data were collected through a rigorous search of academic and technical databases, including:

1. **Academic Databases:** Google Scholar, IEEE Xplore, and ScienceDirect, focusing on keywords such as *Reliability of Military Electronics*, *Environmental Stress*, and *Climate Change Defense*.
2. **Standardization Documents:** A comparative analysis of the evolution of military standards (e.g., the transition from MIL-STD-810G to MIL-STD-810H).
3. **Strategic Reports:** Documents from the Intergovernmental Panel on Climate Change (IPCC) for climate projection data and annual reports from global ministries of defense.

Inclusion and Exclusion Criteria

To ensure high relevance and data integrity, the selected literature met the following criteria:

1. Published within the last 10–15 years to capture the most recent climate change trends.
2. Focused on high-power electronic components or sensitive sensory equipment.
3. Contextualized within tropical operational environments or extreme climate conditions.

Data Analysis Techniques

The gathered data were analyzed through a three-stage process:

1. **Climate Variable Identification:** Extracting data regarding global mean temperature increases and the

frequency of extreme weather events.

2. **Vulnerability**

Mapping: Correlating climate variables with specific technical failure modes in Army equipment (e.g., the impact of extreme drought-induced dust on combat vehicle cooling systems).

3. **Gap Analysis:** Comparing the capabilities of current electronic systems against future environmental demands as identified in existing literature.

Literary Case Study: Army Electronic Equipment

As a unit of analysis, this study examines literature concerning:

1. **Field Communication Systems:** The impact of extreme humidity on the degradation of tactical radio circuits and signal integrity.
2. **Optronic and Sensor Systems:** The influence of prolonged drought-induced haze or fine particulate matter on the accuracy of infrared sensors in armored vehicles.

RESULTS AND DISCUSSIONS

Matrix of Environmental Parameters and the Impacts on Army Electronics

Environmental Parameter	Traditional Design Baseline	Climate Change Projection	Impact on Army Electronics
Extreme Temperature	Maximum +50°C (MIL-STD-810G)	Frequent peaks exceeding +55°C in tropical zones.	Accelerated thermal aging; 50% reliability drop per 10°C rise (USAF, 2014).
Relative Humidity	Intermittent cycles (40-60%).	Persistent saturation (>80%) with heavy rainfall events.	Tin whisker growth and leakage currents in PCBs (Klyatis, 2018).
Atmospheric Salinity	Limited to coastal fringes.	Increased aerosol intrusion further inland due to intensifying storms.	Accelerated galvanic corrosion on connectors and antennas (DTIC, 2019).

Environmental Parameter	Traditional Design Baseline	Climate Change Projection	Impact on Army Electronics
Particulate Matter	Standard coarse dust/sand.	Increase in fine particulates (PM _{2.5}) from extreme droughts.	Static buildup and clogging of active cooling heat sinks (DoD, 2021).
UV Radiation	Standard latitudinal levels.	Higher UV indices due to atmospheric composition changes.	Polymer degradation in external cable insulation and ruggedized casings (IPCC, 2023).

The table above is the result of reviewed literatures, which indicates a significant convergence between shifting climate patterns and the accelerated degradation of Army electronic systems. Findings suggest that the "safe operating envelope" defined in older iterations of military standards, such as MIL-STD-810G, is increasingly being breached by contemporary weather extremities. The primary result of this environmental shift is a reduction in the Mean Time Between Failures (MTBF) for tactical equipment, as current hardware was not engineered to withstand the persistent thermal and hygroscopic stresses now observed in tropical and arid operational area (Pecht, 2009).

Thermal stress emerges as the most critical vulnerability identified in the data. Analysis of the United States Air Force (USAF) Avionics Integrity Program data confirms that thermal-induced failures account for over half of all electronic malfunctions in the field. As ambient temperatures approach and exceed 55°C, the temperature gradient required for effective heat dissipation narrows significantly. For Army assets like the Integrated Fire Control Systems (IFCS) in armored vehicles, this results in "thermal throttling" or total system shutdown, effectively neutralizing technological advantages during peak daylight operations in high-heat environments.

Furthermore, the results highlight a synergistic effect between humidity and salinity that extends beyond coastal operations. Literature from the Defense

Technical Information Center (DTIC, 2019) notes that intensifying storm patterns transport saline aerosols much further inland than previously mapped. When combined with persistent relative humidity above 80%, these aerosols create a conductive electrolyte film on Printed Circuit Boards (PCBs). This facilitates electrochemical migration and the growth of dendritic structures, which lead to intermittent signal failures in high-frequency communication sets—a failure mode that is notoriously difficult to diagnose in field maintenance conditions.

The discussion also points to a critical "modernization gap" in particulate protection. While standard military hardware is ruggedized against coarse sand and dust, the increase in fine particulate matter (PM2.5) resulting from climate-induced droughts presents a different set of challenges. These finer particles can bypass traditional filtration systems, accumulating on internal high-voltage components and causing electrostatic discharge (ESD) or impeding the airflow of micro-fans. This suggests that current filtration and sealing specifications (IP67/IP68) may require re-evaluation to account for the changing physical characteristics of atmospheric dust in drought-prone regions.

Ultimately, the cumulative evidence underscores that climate change acts as a "threat multiplier" for defense logistics. The transition from predictable seasonal cycles to volatile, extreme events means that the maintenance schedules of the past are no longer sufficient. To maintain operational readiness, the literature suggests a shift toward "Prognostics and Health Management" (PHM) systems that use real-time environmental sensors to predict failures before they occur. Without such adaptation, the Army faces a future of escalating lifecycle costs and diminished reliability in the very technologies meant to ensure battlefield superiority.

CONCLUSION

This study demonstrates that climate change is no longer a peripheral environmental issue but a core technical challenge for modern defense electronics. The synthesis of current literature reveals that the escalating frequency of thermal extremes, persistent high humidity, and increased atmospheric salinity significantly encroaches upon the operational safety margins of Army hardware. The traditional reliance on static, historical climate data for engineering specifications is no longer sufficient to guarantee the reliability of mission-critical systems such as tactical communications and fire control units. Ultimately, the accelerated degradation of these components under "new normal" climate conditions threatens to undermine combat readiness and increase the total cost of ownership for defense departments globally.

Strategic Recommendations

To mitigate these emerging risks, the following strategic measures are recommended for defense procurement and maintenance frameworks:

1. **Revision of Procurement Standards:** Defense agencies should move beyond the baseline requirements of MIL-STD-810H and implement "Climate-Plus" specifications. This involves mandating higher thermal tolerance thresholds (up to +65°C or +70°C for internal enclosures) and enhanced hermetic sealing to protect against fine particulate matter and saline intrusion.
2. **Transition to Advanced Material Science:** Investment must be prioritized in **Wide Bandgap (WBG)** semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC). These materials offer superior thermal conductivity and can operate at significantly higher temperatures

than traditional silicon-based components, making them ideal for high-power military electronics in warming climates.

3. **Implementation of Prognostics and Health Management (PHM):** Rather than relying on fixed-interval maintenance, the Army should integrate AI-driven PHM systems. By utilizing embedded environmental sensors to monitor real-time heat and moisture exposure, maintenance can shift to a predictive model, replacing sensitive modules before climate-induced failure occurs on the battlefield.
4. **Infrastructure Adaptation for Storage:** Strategic logistics hubs and forward operating bases must be upgraded with climate-controlled storage facilities. Even when not in active use, electronic assets are susceptible to "dormant degradation" caused by extreme warehouse temperatures and humidity.

By adopting these proactive strategies, the military can ensure that its technological edge remains resilient in the face of an increasingly volatile global climate.

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