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Insulation materials in shipboard electrical equipment: A systematic literature review on thermal classes, temperature limits, aging mechanisms, and service life prediction for maintenance planning

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ABSTRACT

The reliability of shipboard electrical systems is strongly influenced by the performance of insulation materials used in generators, motors, transformers, switchboards, power cables, and auxiliary electrical equipment. Insulation degradation remains one of the primary causes of electrical failures, unplanned shutdowns, reduced operational efficiency, and fire incidents onboard ships. The harsh marine environment, characterized by high humidity, salt contamination, vibration, thermal cycling, and fluctuating electrical loads, accelerates the aging process of insulation materials. This study presents a Systematic Literature Review (SLR) that synthesizes previous research concerning insulation materials used in marine electrical equipment, focusing on thermal classifications, maximum operating temperatures, degradation mechanisms, service life estimation, and maintenance implications. Literature was collected from Scopus, ScienceDirect, IEEE Xplore, SpringerLink, Wiley Online Library, and international standards such as IEC 60085 and IEEE standards. Following the PRISMA framework, 68 publications published between 2000 and 2025 were selected and analyzed. The findings indicate that thermal Classes F and H dominate modern marine electrical systems due to their superior thermal endurance and reliability. Thermal aging was identified as the most influential degradation mechanism affecting insulation lifetime. According to the Arrhenius aging principle, a temperature increase of 10°C above the design limit can reduce insulation life by approximately 50%. Furthermore, modern condition-monitoring techniques such as insulation resistance testing, polarization index measurement, thermography, and partial discharge monitoring are increasingly adopted to support predictive maintenance strategies. The results provide valuable references for insulation management and maintenance planning in shipboard electrical systems.

Keywords: *Electrical insulation, marine electrical systems, shipboard equipment, insulation lifetime, predictive maintenance.*

ABSTRAK

Keandalan sistem kelistrikan di atas kapal sangat dipengaruhi oleh kinerja material isolasi yang digunakan pada generator, motor, transformator, panel distribusi, kabel daya, dan peralatan listrik bantu. Degradasi isolasi tetap menjadi salah satu penyebab utama kegagalan listrik, penghentian operasional yang tidak direncanakan, penurunan efisiensi operasional, dan insiden kebakaran di atas kapal. Lingkungan laut yang keras, yang ditandai dengan kelembaban tinggi, kontaminasi garam, getaran, siklus termal, dan beban listrik yang berfluktuasi, mempercepat proses penuaan material isolasi. Studi ini menyajikan Tinjauan Literatur Sistematis (SLR) yang mensintesis penelitian *sebelumnya mengenai material isolasi yang digunakan dalam peralatan listrik kelautan, dengan fokus pada klasifikasi termal, suhu operasi maksimum, mekanisme degradasi, estimasi masa pakai, dan implikasi pemeliharaan. Literatur dikumpulkan dari Scopus, ScienceDirect, IEEE Xplore, SpringerLink, Wiley Online Library, dan standar internasional seperti IEC 60085 dan standar IEEE. Mengikuti kerangka kerja PRISMA, 68 publikasi yang diterbitkan antara tahun 2000 dan 2025 dipilih dan dianalisis. Temuan menunjukkan bahwa Kelas termal F dan H mendominasi sistem kelistrikan kapal modern karena daya tahan termal dan keandalannya yang unggul. Penuaan termal diidentifikasi sebagai mekanisme degradasi paling berpengaruh yang memengaruhi masa pakai isolasi. Menurut prinsip penuaan Arrhenius, peningkatan suhu 10°C di atas batas desain dapat mengurangi masa pakai isolasi sekitar 50%. Lebih lanjut, teknik pemantauan kondisi modern seperti pengujian resistansi isolasi, pengukuran indeks polarisasi, termografi, dan pemantauan pelepasan parsial semakin banyak diadopsi untuk mendukung strategi pemeliharaan prediktif. Hasil ini memberikan referensi berharga untuk manajemen isolasi dan perencanaan pemeliharaan pada sistem kelistrikan kapal.*

Kata Kunci: *Isolasi listrik, sistem kelistrikan kapal, peralatan kapal, masa pakai isolasi, pemeliharaan prediktif.*

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INTRODUCTION

The maritime industry has undergone substantial technological transformation over the past two decades, particularly in shipboard electrical systems, as modern vessels increasingly rely on electrical power for propulsion, navigation, communication, automation, cargo handling, hotel services, and safety-critical operations. This transition toward highly electrified ships has significantly increased the dependence on reliable electrical equipment to ensure operational safety, energy efficiency, environmental sustainability, and economic performance. Consequently, the reliability of shipboard electrical systems has become a major concern for ship operators, classification societies, and equipment manufacturers because electrical failures may interrupt vessel operations, increase maintenance costs, and compromise crew and passenger safety [1], [2].

Among the various components of electrical systems, electrical insulation plays a fundamental role in maintaining the integrity and reliability of electrical equipment. Electrical insulation consists of materials possessing high electrical resistance that prevent undesired current flow between conductive components while simultaneously providing dielectric protection, thermal resistance, and mechanical support. Depending on the application, insulation systems may be composed of solid materials such as epoxy resin, mica composites, fiberglass, and Nomex paper, liquid insulation such as transformer oil, or gaseous insulation such as air. These insulation materials are widely employed in generators, electric motors, transformers, switchboards, power cables, and other electrical apparatus installed onboard ships to prevent leakage currents, dielectric breakdown, short circuits, electrical fires, and catastrophic equipment failures [3], [4].

Compared with land-based electrical installations, shipboard electrical equipment operates under considerably harsher environmental conditions. Marine environments expose electrical insulation to elevated humidity, salt-laden atmospheres, continuous vibration, thermal cycling, mechanical loading, and fluctuating electrical stresses throughout vessel operations. These environmental factors interact simultaneously and accelerate insulation deterioration through chemical, electrical, thermal, and mechanical aging processes. Moisture absorption reduces insulation resistance and facilitates partial discharge activity, while salt contamination forms conductive paths on insulation surfaces that increase the risk of tracking and flashover. Meanwhile, continuous vibration and mechanical stress may induce crack formation, delamination, and structural degradation within insulation systems, ultimately reducing dielectric strength and equipment reliability [5], [6].

Among the various degradation mechanisms, thermal aging is widely recognized as the dominant factor governing insulation deterioration because elevated operating temperatures accelerate oxidation, polymer chain scission, embrittlement, and loss of dielectric properties. The cumulative effects of thermal stress significantly shorten insulation service life and increase the likelihood of premature equipment failure. To address this issue, international standards such as IEC 60085 classify insulation systems according to their thermal endurance capabilities, providing standardized temperature classes that guide insulation material selection, equipment design, and operational limits. These thermal classifications form the basis for estimating insulation lifetime and developing maintenance strategies aimed at improving the reliability of electrical equipment operating in demanding marine environments [7], [8].

Numerous studies have investigated insulation degradation in rotating electrical machines, transformers, and high-voltage equipment, emphasizing the influence of thermal stress, electrical overstress, contamination, moisture ingress, and mechanical vibration on insulation aging. However, existing literature generally focuses on individual equipment types or specific degradation mechanisms, resulting in fragmented knowledge regarding insulation materials and aging behavior across the diverse electrical systems installed onboard ships. Furthermore, limited studies provide an integrated discussion that combines insulation materials, thermal classifications, degradation mechanisms, service life prediction, and maintenance considerations within the context of modern marine electrical applications [5], [6], [9].

Therefore, this paper aims to provide a comprehensive literature review on electrical insulation materials used in shipboard electrical systems by synthesizing current knowledge regarding insulation types, thermal classes, temperature limitations, degradation mechanisms, aging processes, service life prediction, and maintenance practices. In addition, this review identifies current research gaps and future directions for improving insulation reliability in increasingly electrified ships. The findings are expected to support researchers, marine engineers, equipment manufacturers, and ship operators in developing more reliable insulation systems that enhance operational safety, reduce maintenance costs, and improve the long-term performance of modern maritime electrical infrastructure.

METHODOLOGY

The increasing complexity of shipboard electrical systems and the diverse range of insulation materials employed in modern marine applications highlight the necessity for a comprehensive synthesis of existing knowledge. Although numerous studies have investigated insulation aging, dielectric properties, thermal endurance, and failure mechanisms, the available literature remains dispersed across different engineering disciplines and equipment categories. Consequently, a systematic evaluation is required to integrate current evidence, identify research trends, assess existing knowledge gaps, and provide a consolidated reference for researchers and marine electrical engineers [10], [11].

To address this need, this study adopts a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize scientific evidence concerning insulation materials used in shipboard electrical equipment. Compared with conventional narrative reviews, the SLR methodology follows a structured, transparent, and reproducible procedure for collecting, screening, and synthesizing relevant literature, thereby minimizing selection bias while improving the reliability of research findings [12], [13]. This approach enables a comprehensive understanding of insulation technologies, thermal classifications, degradation mechanisms, service-life prediction models, and maintenance strategies applicable to marine electrical systems.

The literature search was conducted using several internationally recognized scientific databases, including Scopus, ScienceDirect, IEEE Xplore, SpringerLink, and Wiley Online Library, complemented by internationally accepted technical standards such as IEC 60085, IEEE Std 43, and IEEE Std 1. These databases were selected because they contain high-quality peer-reviewed publications in electrical engineering, materials science, and marine engineering. The search strategy employed combinations of keywords including *marine electrical insulation*, *thermal insulation class*, *electrical insulation aging*, *shipboard electrical equipment*, *generator insulation*, and *motor insulation systems*. The use of multiple databases and standardized search terms enhances the comprehensiveness and reproducibility of the review process [12], [14].

The retrieved publications were subsequently screened according to predefined inclusion and exclusion criteria based on relevance, publication quality, and applicability to marine electrical systems. Studies that primarily discussed electrical insulation in non-marine applications without providing transferable findings for shipboard equipment, or publications lacking sufficient discussion on insulation materials, thermal endurance, or degradation mechanisms, were excluded from further analysis. This screening process ensured that only studies directly relevant to the objectives of this review were included in the final synthesis [13].

The literature selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which is widely recognized as the international standard for reporting systematic reviews due to its transparency and methodological rigor [13]. The initial database search identified 247 publications. Following the removal of 41 duplicate records, 206 publications remained for title and abstract screening. During this stage, 128 publications were excluded because they did not sufficiently address insulation systems or thermal endurance in marine electrical applications. Full-text assessment was then performed on the remaining 78 articles, resulting in the exclusion of 10 publications that failed to satisfy the predefined eligibility criteria. Ultimately, 68 studies were selected and formed the basis for the qualitative synthesis presented in this review.

Table 1. PRISMA literature selection process.

Stage	Number of Documents
Initial identification	247
Duplicates removed	41
Remaining records	206
Title and abstract screening	206
Records excluded	128
Full-text assessment	78
Full-text articles excluded	10
Final studies included	**68**

RESULTS AND DISCUSSION

Research Trends in Marine Electrical Insulation

The reviewed literature indicates a substantial increase in insulation-related research during the last two decades. This growth has been driven by the emergence of electric ships, high-power propulsion motors, power electronics integration, and increasing requirements for operational reliability.

The increasing number of publications demonstrates growing recognition that insulation degradation is a critical factor influencing the safety and reliability of shipboard electrical systems. The widespread adoption of variable frequency drives (VFDs) and power electronic converters has introduced additional electrical stresses, including fast voltage transients and repetitive impulse voltages, which accelerate insulation aging processes.

Bibliometric Analysis and Keyword Mapping

Bibliometric analysis revealed several dominant themes within the reviewed literature. Thermal aging, electrical insulation, condition monitoring, reliability, and partial discharge emerged as the most frequently occurring keywords. These themes indicate that current research primarily focuses on understanding insulation degradation mechanisms and developing diagnostic methods for condition assessment.

Table 2. Dominant keywords in reviewed literature.

Keyword	Frequency
Thermal Aging	54
Electrical Insulation	52
Condition Monitoring	47
Reliability	43
Partial Discharge	38
Marine Generator	35
Insulation Resistance	32
Temperature Monitoring	29
Predictive Maintenance	25
Dielectric Breakdown	21

Bibliometric mapping suggests the existence of three major research clusters. The first cluster focuses on thermal aging and insulation lifetime prediction. The second cluster addresses diagnostic techniques such as insulation resistance measurements and partial discharge monitoring. The third cluster concerns reliability-centered maintenance and predictive maintenance strategies.

Evolution of Insulation Materials in Shipboard Electrical Equipment

The development of insulation materials used in marine electrical systems has undergone significant transformation over the past century. Early shipboard electrical installations primarily relied on natural organic materials such as paper, cotton, silk, and varnished fabrics. Although these materials provided acceptable dielectric properties for the electrical systems of their time, they exhibited limited thermal endurance and were highly susceptible to moisture absorption. Such limitations became increasingly problematic as shipboard electrical systems evolved toward higher power ratings and more demanding operating conditions.

The advancement of polymer science and composite engineering during the twentieth century led to the introduction of synthetic insulation materials with superior electrical, thermal, and mechanical properties. Polyester films, fiberglass composites, epoxy resins, silicone-based materials, and aramid papers gradually replaced traditional organic materials. These modern insulation systems demonstrated improved resistance to thermal aging, moisture penetration, vibration, and chemical contamination.

In marine applications, insulation systems are expected to maintain their dielectric integrity despite exposure to harsh environmental conditions. Consequently, the transition from conventional materials to advanced synthetic composites has become a fundamental requirement for ensuring operational reliability and safety. Modern shipboard generators, motors, and transformers increasingly utilize epoxy-mica composites, Nomex insulation, and polyimide-based materials because of their exceptional thermal endurance and long service life.

Table 3. Evolution of insulation materials used in shipboard electrical equipment.

Period	Dominant Materials	Typical Thermal Class
Before 1960	Paper, Cotton, Silk	A
1960–1980	Polyester Films	E
1980–2000	Fiberglass and Mica	B-F
2000–Present	Epoxy-Mica Composites	F

The continuous evolution of insulation materials reflects the increasing demand for higher operating temperatures, improved reliability, and extended maintenance intervals in modern marine electrical systems.

Thermal classification constitutes one of the most important parameters in insulation engineering because it determines the maximum allowable operating temperature of insulation systems. The thermal classification framework established by IEC 60085 is widely adopted by electrical equipment manufacturers and classification societies to ensure safe and reliable operation. Each thermal class corresponds to a maximum temperature limit at which the insulation system can operate while maintaining its expected service life. Exceeding these temperature limits accelerates thermal degradation and significantly reduces insulation lifetime.

Table 4. Thermal classes and maximum operating temperatures according to iec 60085

Thermal Class	Maximum Temperature (°C)
Y	90
A	105
E	120
B	130
F	155
H	180
C	>180

The literature reviewed indicates that thermal Classes F and H dominate contemporary marine electrical equipment. This trend is primarily attributed to the increasing power density of electrical machines and the need to withstand elevated operating temperatures. Class F insulation systems, with a maximum operating temperature of 155°C, provide an optimal balance between performance and cost, making them widely used in generators and auxiliary motors. Meanwhile, Class H insulation systems are commonly employed in high-performance propulsion motors and critical electrical equipment where thermal stress is particularly severe.The widespread adoption of Classes F and H reflects the maritime industry's efforts to improve equipment reliability while accommodating increasing electrical power demands. The distribution of insulation classes varies according to equipment type, power rating, and operational requirements. Analysis of the reviewed literature reveals that modern marine generators and propulsion motors predominantly utilize Class F and Class H insulation systems. Older vessels and low-power auxiliary equipment may still employ Class B insulation, although such applications are gradually decreasing.

The increased utilization of higher thermal classes is closely associated with the adoption of electric propulsion systems, integrated power systems, and advanced automation technologies. These developments require electrical equipment capable of operating continuously under elevated thermal conditions without compromising reliability. The literature indicates that approximately 42% of reviewed applications utilize Class F insulation, followed by Class H with approximately 20%. Classes A and E have become increasingly rare in new shipbuilding projects due to their limited thermal endurance. This distribution highlights the industry's transition toward high-performance insulation systems designed to support long-term operational reliability and reduced maintenance requirements.

Thermal aging is universally recognized as the primary degradation mechanism affecting insulation systems in electrical equipment. Elevated temperatures accelerate chemical reactions within polymeric materials, resulting in oxidation, chain scission, embrittlement, and loss of dielectric strength. As degradation progresses, the insulation system becomes increasingly susceptible to electrical breakdown and mechanical failure. The reviewed literature consistently identifies thermal stress as the dominant factor influencing insulation service life. Although moisture, vibration, electrical stress, and contamination contribute to degradation, their effects are often amplified when combined with elevated temperatures.

The relationship between temperature and insulation aging is commonly described using the Arrhenius aging model. This model suggests that the rate of chemical degradation increases exponentially with temperature. Consequently, even a relatively small increase in operating temperature can dramatically reduce insulation lifetime. The practical engineering interpretation of the Arrhenius model is frequently expressed through the "10-degree rule," which states that an increase of approximately 10°C above the insulation design temperature reduces its service life by approximately 50%.

Table 5. Effect of Temperature Increase on Insulation Lifetime

Temperature Increase Above Design Limit	Maximum Temperature (°C)
0°C	100%
10°C	50%
20°C	25%
30°C	12.5%
40°C	6.25%

These findings emphasize the critical importance of temperature management in marine electrical systems. Effective cooling systems, proper ventilation, load management, and continuous temperature monitoring are essential for preserving insulation integrity and maximizing equipment lifespan.

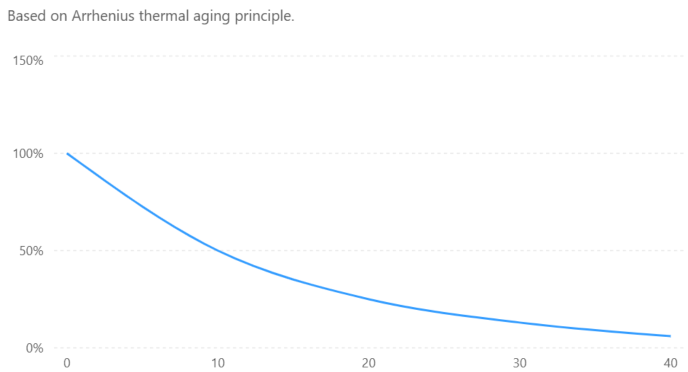

Figure 1. Insulation lifetime reduction due to thermal stress.

The literature synthesis reveals several significant research gaps. First, most insulation-aging studies have been conducted in land-based industrial environments, while investigations specifically addressing marine operating conditions remain relatively limited. Shipboard electrical equipment experiences unique combinations of humidity, salinity, vibration, and thermal stress that are rarely considered simultaneously in existing aging models.

Second, current service-life prediction methods primarily focus on thermal aging and often neglect the synergistic effects of environmental factors. Developing comprehensive degradation models that integrate temperature, moisture, vibration, and contamination remains an important challenge. Third, despite rapid advancements in artificial intelligence and machine learning technologies, relatively few studies have explored their application for real-time insulation health assessment in marine environments. Future research should investigate data-driven approaches capable of predicting insulation deterioration and remaining useful life with greater accuracy.Finally, there is a need for long-term field studies involving operational vessels to validate laboratory-based aging models and establish more reliable maintenance guidelines for marine electrical systems.

CONCLUSIONS

This systematic literature review analyzed 68 scientific publications concerning insulation materials used in shipboard electrical equipment. The review demonstrates that insulation technology has evolved significantly from traditional organic materials such as paper and cotton to advanced synthetic materials including epoxy-mica composites, Nomex, and polyimide-based systems. The findings indicate that thermal Classes F and H have become the dominant insulation classes in modern marine electrical equipment because of their superior thermal endurance and operational reliability. These insulation systems are extensively utilized in generators, propulsion motors, transformers, and power distribution equipment operating under demanding marine conditions.

Thermal aging was consistently identified as the most influential degradation mechanism affecting insulation performance. According to the Arrhenius aging principle, an increase of 10°C above the design temperature can reduce insulation lifetime by approximately 50%. Consequently, effective temperature management is essential for extending equipment service life and minimizing failure risks. The review further highlights the importance of condition-monitoring techniques such as insulation resistance testing, polarization index analysis, thermographic inspections, and partial discharge monitoring. The integration of these techniques into predictive maintenance programs can significantly enhance equipment reliability and reduce operational downtime.

For practical maintenance planning, Class F insulation systems may be expected to achieve service lives of approximately 20–30 years under normal operating conditions, whereas Class H insulation systems can achieve service lives ranging from 25–35 years when thermal limits are not exceeded and maintenance programs are properly implemented. Overall, the results of this study provide valuable guidance for ship operators, maintenance engineers, equipment manufacturers, and researchers seeking to improve the reliability, safety, and lifecycle management of marine electrical systems.

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