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Integrated Sensing and Communications for Small UAV Applications in CELLULAR NETWORKS

In-Flight UV-C Disinfection After COVID-19

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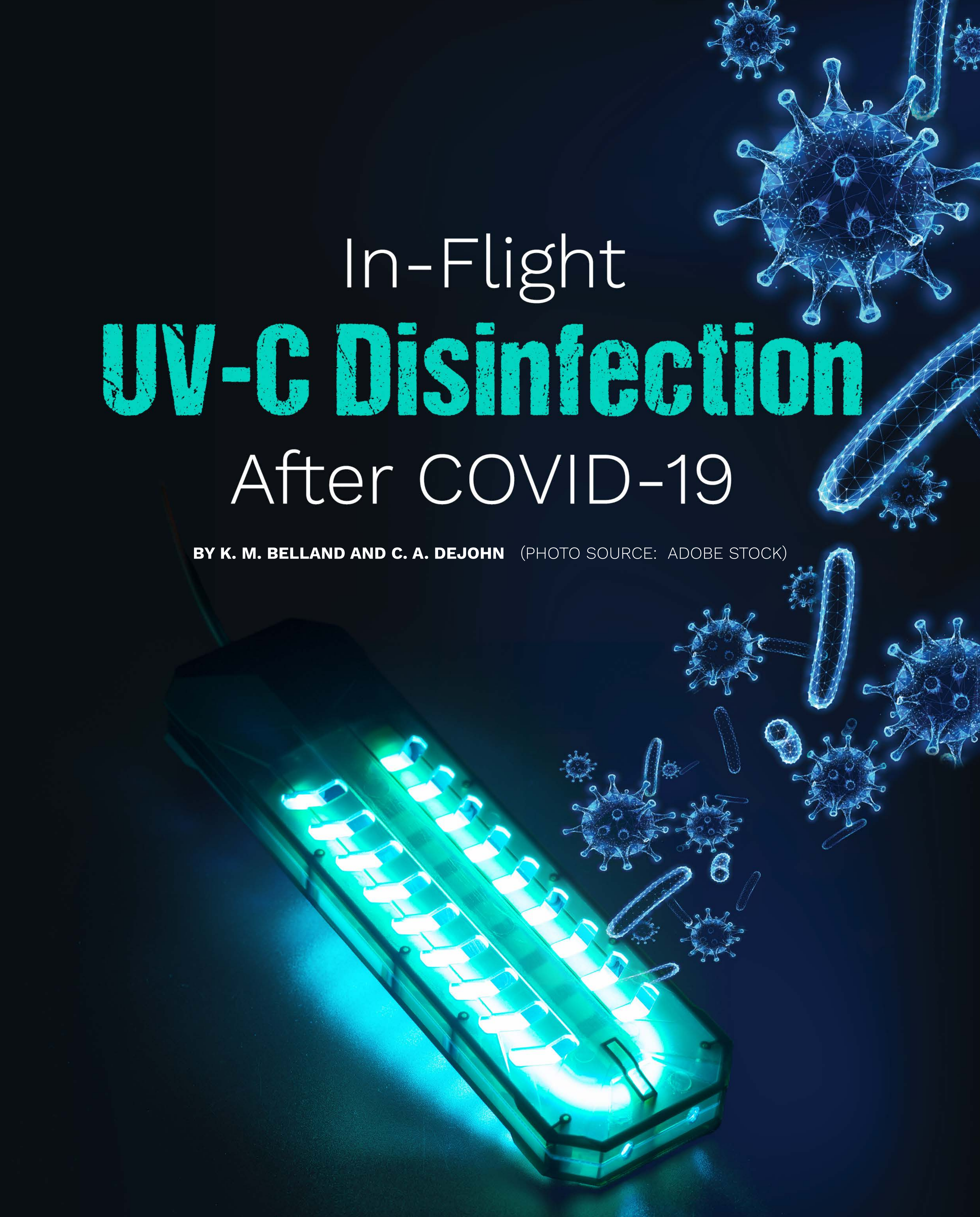

PROBLEM STATEMENT

Although rare, aircraft cabins have been associated with disease transmission, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and influenza A. A recent risk-benefit analysis estimates that such transmissions have led to up to 10,000 deaths annually (from 2020 to 2023) and a $200 billion economic burden. Ultraviolet-C (UV-C) air disinfection could mitigate up to 80% of these impacts, enhancing passenger safety and reducing transmission [1–4].

INTRODUCTION

The aviation industry seeks effective cabin disinfection strategies, with UV-C offering a chemical-free solution to reduce disease transmission. This article examines UV-C's effectiveness, safety, risks, benefits, and regulatory considerations compared to other methods.

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LITERATURE REVIEW

Researchers have become increasingly intrigued by UV-C disinfection as a tool to reduce the spread of infectious agents, both on surfaces and in the air. Existing studies point to UV-C's ability to lower infection rates, cut healthcare costs, and keep workforces healthy. Questions remain about its overall safety, cost-effectiveness, and best-use scenarios. In the sections that follow, UV-C technology's strengths and weaknesses will be explored.

Historical Background on UV-C Disinfection

Researchers recognized the impact of light on microorganisms as early as 1845, with a breakthrough in 1877 showing sunlight inhibited microorganism growth in Pasteur's solution. Studies later found shorter wavelengths to be most effective. In 1933, the concept of airborne infection via droplet nuclei emerged, and by 1935, experiments confirmed ultraviolet germicidal irradiation (UVGI) deactivated airborne microorganisms. The 1960s and 1970s saw the introduction of upper-room UVGI, followed by extensive efforts in the 1990s to evaluate its efficacy and safety [5].

UV-C light has long been used for water treatment and air purification, including during World War II for disinfecting hospitals and military facilities. Advancements in the 1950s boosted its accessibility, leading to its widespread adoption today for decontamination. Far-UVC light shows potential for safely inactivating airborne pathogens in occupied spaces [6–8]. UV-C supplements other disinfection methods by neutralizing bacteria, viruses, and pathogens [9, 10]. During the coronavirus disease 2019 (COVID-19) pandemic, UV technologies were crucial for decontaminating personal protective equipment and reducing pathogens on aircraft surfaces [9, 11].

UV-C Disinfection in Aviation

The aviation industry's interest in UV-C disinfection emerged recently to address disease transmission and translocation risks in aircraft. The SARS outbreak, H1N1 (swine flu) pandemic, and COVID-19 pandemic underscored the vulnerability of enclosed spaces like aircraft cabins. These events led to exploring UV-C as a supplementary disinfection method with manual cleaning and high-efficiency particulate air (HEPA) filtration. The United Nations International Civil Aviation Organization (ICAO) and Collaborative Arrangement for the Prevention and Management of Public Health Events in Civil Aviation applied the James Reason Swiss Cheese Model for layered risk mitigation during the COVID-19 pandemic. UV-C proved highly effective against bacteria, viruses, and spores, enhancing air quality and surface disinfection [1].

There is increasing interest in using continuous UV light during flights instead of episodic disinfection between flights. UV-C light can reduce airborne transmission risk in aircraft cabins by up to 90% by targeting pathogens in the air. Using Direct Irradiation Below the Exposure Level (DIBEL) technology enables safe inactivation of pathogens in occupied cabins during flight [3, 12].

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Comparative Analysis of Disinfection Methods

Several disinfection methods are used in aircraft, each with strengths and limitations. These methods are as follows:

- **Manual Cleaning and Chemical Disinfection:** Manual cleaning with chemical disinfectants effectively reduces surface contamination but has limitations, including variability in thoroughness, recontamination risks, and potential environmental and toxic effects [1, 4]. Additionally, proper contact or "dwell time" is crucial for efficacy, as insufficient contact time can leave pathogens behind and potentially spread infections.

- **HEPA Filtration:** HEPA filters, common in commercial aircraft, effectively capture particles 0.3 µm or larger, including submicron viruses like SARS-CoV-2 [13]. However, their efficiency depends on airflow, leaving areas of reduced circulation like near seats and aisles at higher risk [1, 3, 14]. HEPA filters do not address surface contamination and are less effective for particles around 0.15 µm, a size linked to SARS-CoV-2 [13]. Studies confirm that airborne transmission risks persist even with the use of HEPA filtration systems [14].

To address these concerns, UV-C technology has emerged as an essential tool for enhancing air quality and infection control, aligning with the American Society of Heating Refrigeration and Airconditioning Engineers (ASHRAE) standards that emphasize maintaining safe and healthy indoor environments. ASHRAE recognizes the effectiveness of UV-C disinfection in reducing airborne pathogens, particularly when integrated into HVAC systems [13]. UV-C systems are frequently employed to sanitize components of air-handling units, effectively preventing microbial growth that can degrade air quality. The implementation of UV-C technology supports ASHRAE's commitment to improving ventilation, filtration, and air cleaning, thereby mitigating the spread of infectious diseases. This proven, energy-efficient solution complements other mechanical ventilation strategies, offering a robust approach to maintaining healthier indoor environments [13].

- **UV-C Disinfection:** UV-C light provides several advantages over traditional methods, including rapid, residue-free disinfection of airborne and surface pathogens. It can be automated to reduce human error and sanitize aircraft cabins in minutes, improving efficiency. For example, SARS and influenza A can be 90% inactivated within 15 minutes in occupied cabins [4]. Combined with HEPA filtration, UV-C ensures continuous in-flight air and surface disinfection, addressing risks from infected passengers boarding post-cleaning [1, 4].

Unlike vaccines, which require time to develop and adapt to mutations, UV-C light acts immediately and is effective against a broad spectrum of viruses, including many known human pathogens, by damaging their genetic material (DNA or RNA). While UV-C light is highly effective, viruses like those causing diseases such as COVID-19 can mutate over time. These mutations may alter the virus's structure, potentially impacting the efficacy of UV-C in inactivating them, although UV-C's broad mechanism of action generally limits this risk.

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EFFECTIVENESS OF UV-C IN PATHOGEN INACTIVATION

UV-C light effectively inactivates microorganisms by damaging their DNA or RNA, preventing replication, and it is effective against bacteria, viruses, and fungi [15]. Studies show UV-C can significantly reduce airborne pathogens in aircraft cabins, lowering disease transmission risks [16]. A cost-benefit analysis found that combining continuous UV-C disinfection with HEPA filtration and mask-wearing could reduce in-flight transmission of SARS-CoV-2 and influenza A by up to 98% [1, 4].

A prepublication analysis estimates that due to the combined transmission of SARS-CoV-2 and influenza A aboard commercial aircraft in the United States from 2020 to 2023, there were about 10,000 annual deaths, declining to 3,000/year going forward and creating an estimated annual economic burden of $200 billion [3]. Up to 80% of the deaths and economic burden might be saved by supplementing the typical 30 air changes per hour of the aircraft ventilation system with a presently available 120 air changes per hour by using a UV-C disinfection system. The risks due to accidental overexposure to UV-C are orders of magnitude lower than the benefits. The 0.00003% risk of acute (one-time) overexposure for any given passenger may result in a 1–2-day skin or eye irritation, with no long-term effects or risks. This compares to the 15,000× greater risk at 0.5% of contracting COVID-19 or influenza A that persists for several days to weeks and carries a risk of hospitalization or death. The estimated risk of nonmelanoma skin cancer is virtually nil.

SAFETY CONCERNS AND MITIGATION STRATEGIES

While effective, UV-C disinfection poses safety risks, such as skin and eye damage from prolonged exposure, including erythema and photokeratitis [15]. In aircraft cabins, these risks are addressed by using far-UV-C light, which is less penetrating and therefore safer, and using engineering controls that limit exposure to safe exposure levels. Automated systems with redundant safety features like passive infrared, ultrasound, and light detection and ranging sensors (LIDAR) can shut off UV-C emitters when individuals are detected nearby, thus enhancing safety [17].

SUMMARY OF FINDINGS

The literature shows UV-C disinfection effectively reduces airborne and surface pathogens in aircraft cabins. Its advantages include continuous disinfection without harmful chemicals and improved efficiency, making it a valuable addition to aviation protocols. However, implementation requires careful engineering, maintenance, and adherence to safety limits, with advanced controls to mitigate risks [1, 4].

UV-C DISINFECTION IN AIRCRAFT CABINS

As air travel rebounds and aircraft cabins remain densely populated for hours on end, the need for robust infection-control measures is more pressing than ever. UV-C disinfection offers a scientifically validated means of curbing both airborne and surface pathogens in real time. Although it has garnered praise for enhancing passenger safety and reducing infection rates, considerations such as financial viability, operational logistics, and practical limitations must also factor into the decision-making process. The following subsections will weigh the benefits and challenges to provide a balanced perspective on UV-C's role in fostering safer skies.

Mechanisms of UV-C Disinfection

UV-C light in the germicidal range of 200–280 nm damages the genetic material of pathogens through pyrimidine dimer formation (as shown in Figure 1), preventing replication and effectively inactivating them [16, 18].

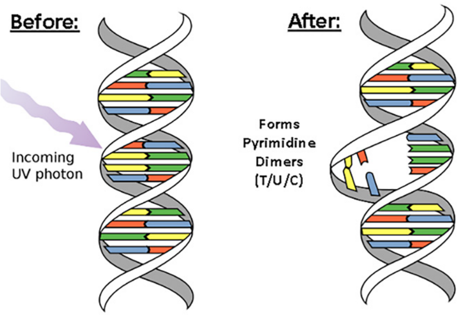

Figure 1. Inactivation of a Virus by UV-C Light *(Source: Allen [19])*.

Implementation in Aircraft Environments

Aircraft cabins, with confined spaces, high passenger density, and limited airflow (shadow spaces), pose challenges for disinfection. UV-C disinfection addresses these effectively by continuously sanitizing air and surfaces. The low humidity in aircraft cabins at cruise altitude dries out the mucous membranes of the respiratory tract, reducing their effectiveness in trapping and neutralizing airborne pathogens. This increases the risk of viral infection and replication. Additionally, dry cabin air causes virus-laden aerosols to lose moisture, stripping away their protective barrier that typically slows transmission and shields against natural UV light. In aircraft cabins, where UV-A and UV-B light are absent, these desiccated aerosols remain airborne longer (as shown in Figure 2), further elevating the risk of transmission. The combination of impaired mucous membranes and prolonged aerosol suspension creates an environment conducive to the rapid spread of airborne viruses [1].

The lack of moisture around viruses facilitates direct transmission, highlighting the need for enhanced disinfection measures during these critical periods.

Advantages Over Traditional Methods

UV-C disinfection offers several advantages over traditional methods, making it an attractive option for use in aircraft cabins.

- **Continuous Disinfection:** Unlike manual cleaning or chemical disinfection between flights, UV-C systems continuously disinfect during flights, reducing recontamination risks from infected passengers [15]. This avoids extending ground time and potential scheduling delays.
- **Chemical-Free Disinfection:** UV-C disinfection avoids chemical residues, protecting passengers, crew, and sensitive aircraft materials and making it safer and more eco-friendly than chemical disinfectants [17].
- **Rapid and Effective Pathogen Inactivation:** UV-C light can inactivate pathogens within minutes during initial cabin decontamination, resulting in quick turnarounds and improving efficiency in flight scheduling [12, 21].
- **Reduction of Human Error:** Automated UV-C systems minimize human error and standardize

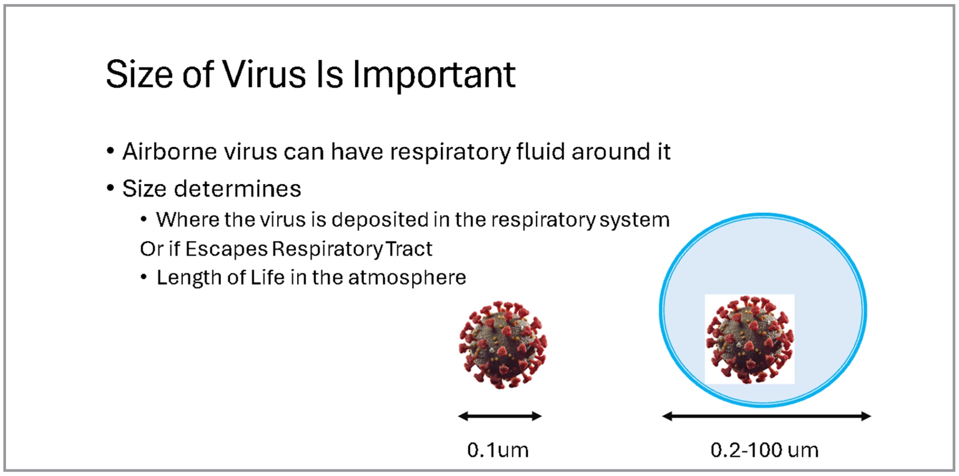

Figure 2. Comparing Virus Size With and Without Respiratory Fluid Retention *(Source: Belland et al. [20])*.

disinfection, ensuring consistent, thorough coverage across the cabin [1].

Challenges and Considerations

While UV-C disinfection offers significant benefits, its implementation in aircraft cabins must be carefully managed to address several challenges.

- **Safety Concerns:** The primary safety concern with UV-C disinfection is overexposure, which can cause skin burns (dermatitis/sunburn) and eye injuries (photokeratitis). Strict engineering controls and safer far-UV-C light, because of its limited penetration, mitigate these risks and enable continuous disinfection [17].
- **Engineering Controls:** Implementing UV-C disinfection in aircraft cabins requires sophisticated engineering solutions to ensure that UV-C light is effective while remaining within safe exposure limits. This includes the use of sensors and automated systems that can detect when passengers or crew are present and adjust the intensity or turn off the UV-C light to prevent overexposure [1].
- **Integration With Existing Systems:** UV-C systems must integrate with aircraft ventilation and lighting without affecting operational efficiency, requiring careful design and testing for compatibility [1].
- **Cost and Maintenance:** Installing and maintaining UV-C systems represents increased cost and weight, but advances in technology are expected to offset these costs and improve accessibility for airlines [1].

Conclusion

UV-C disinfection offers continuous, chemical-free air and surface sanitization, thus enhancing passenger safety against airborne diseases. Effective implementation requires addressing safety, engineering, and cost challenges. As technology advances, UV-C is set to play a growing role in aviation health measures [1].

CURRENT APPLICATIONS AND CASE STUDIES IN THE AVIATION INDUSTRY

The integration of UV-C disinfection technology in the aviation industry has gained significant traction, particularly in response to the COVID-19 pandemic.

Current Applications

Airlines and aircraft manufacturers have explored the following various applications of UV-C to enhance cabin hygiene and reduce the risk of disease transmission during flights:

- **Robotic UV-C Disinfection Systems:** Airlines like Swiss International Air Lines and JetBlue Airways have used robotic UV-C systems to sanitize cabins, autonomously disinfecting high-touch areas like tray tables and lavatories [1].
- **UV-C Integration With HVAC Systems:** UV-C technology, integrated into aircraft HVAC systems, continuously disinfects recirculated air to enhance quality and reduce pathogens. As an example, Boeing has explored the use of UV-C within its HVAC systems to enhance air quality and reduce airborne pathogens [1].
- **Far-UV-C Continuous Disinfection:** Far-UV-C light, safer for human exposure, enables continuous in-flight disinfection. Tested configurations include ceiling-mounted units for air pathogen inactivation [1].

Case Studies

The following case studies describe the different UV-C methods used in the airline industry for sanitizing and disinfecting surfaces:

- **JetBlue Airways – UV-C Robotic Disinfection:** JetBlue Airways, partnering with Honeywell, introduced the Honeywell UV Cabin System for rapid UV-C disinfection of aircraft interiors between flights, sanitizing high-touch surfaces in under 10 minutes and significantly reducing turnaround times [1, 4].

- **Qatar Airways – Comprehensive UV-C Implementation:** Qatar Airways adopted a UV-C strategy integrating robotic surface disinfection with the HVAC. UV-C robots were deployed for surface disinfection. The HVAC systems were upgraded to include UV-C emitters that continuously disinfected recirculated air, reducing the risk of in-flight transmission of COVID-19 and other infectious diseases [1].
- **Boeing – UV-C Wand and Far-UV-C Research:** Boeing developed and tested a UV-C wand as part of its "Confident Travel Initiative," aimed at improving passenger safety during the pandemic. The UV-C wand was designed for manual use by cleaning crews to disinfect surfaces in the aircraft cabin.
- **DIBEL –** DIBEL is currently being utilized in various settings, including high-traffic public spaces like airports, healthcare facilities, schools, and industrial workplaces. The following are examples where DIBEL is being used:
  - Multiple dental offices employing UV-C technologies
  - Public buildings (e.g., town of Southbury, CT)
  - Cast Nylons Ltd.
  - North Canton City Civic Center
  - The Long Island Aquarium
  - REV Fire Group
  - Gillette Stadium (e.g., New England Patriots)
  - Otis Elevator
  - Columbia University Irving Medical Center

ENGINEERING AND DESIGN CONSIDERATIONS

The successful implementation of UV-C disinfection systems in aircraft cabins requires careful consideration of several engineering and design factors. These considerations ensure that UV-C technology is both effective in inactivating pathogens and safe for passengers and crew.

System Integration With Aircraft Infrastructure

A key challenge in implementing UV-C disinfection is integrating it with HVAC, lighting, and structural systems, ensuring compatibility within the limited space of aircraft cabins and cargo areas. The following are examples of systems that would benefit from UV-C implementation:

- **Ventilation Systems:** Integrating UV-C with HVAC systems enables continuous air disinfection and requires precise lamp placement, light intensity, and airflow design to ensure effectiveness while avoiding passenger exposure [1].
- **Lighting Systems:** UV-C emitters can integrate with aircraft lighting by using ceiling or wall-mounted designs to disinfect surfaces. Advanced optics focus light on high-touch areas while minimizing exposure risks [1].

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>
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Safety Mechanisms and Exposure Limits

Passenger and crew safety is paramount when designing UV-C disinfection systems for aircraft. Overexposure to UV-C light can cause skin burns and eye injuries, necessitating the implementation of the following robust safety mechanisms:

- **Exposure Controls:** UV-C systems require sensors to deactivate UV-C lights when passengers or crew are present. Designed for continuous operation during flights, far-UV-C systems must be calibrated to emit light at wavelengths and intensities safe for human exposure [17].
- **DIBEL:** DIBEL is a critical concept when discussing the safety of UV-C light-emitting diodes (LEDs), which emit ultraviolet light primarily in the 200–280-nm range. UV-C light

is highly effective in disinfection and sterilization because it can destroy the DNA and RNA of microorganisms, making it a popular choice for applications in healthcare, water purification, and surface disinfection [1, 4].

- **Redundant Safety Systems:** Redundant safety systems like LIDAR, ultrasound, and passive infrared sensors detect human presence and shut off UV-C emitters automatically. To deactivate the system in case of an emergency, manual override controls provide additional safety [1].

Operational Considerations

The operational efficiency of UV-C systems in aircraft depends on several factors, including durability and maintenance and energy consumption. These factors are described as follows:

- **Durability and Maintenance:** UV-C systems must be durable to withstand frequent flights, vibrations, and environmental changes. Components should be easy to maintain and replace with minimal downtime and be supported by regular maintenance schedules to ensure efficiency and timely repairs [1].
- **Energy Consumption:** UV-C systems should be energy efficient to minimize aircraft electrical demands. UV-C LEDs, with lower power use and heat output, are a promising alternative to mercury-vapor lamps. Optimal placement and scheduling can further reduce energy consumption while ensuring effective disinfection [1].

Design for Redundancy

UV-C systems must prioritize redundancy and reliability for cabin hygiene. Redundant emitters and real-time monitoring (as shown in Figure 3) ensure continuous disinfection during flights [1].

Compliance With Regulatory Standards

Aircraft UV-C disinfection systems must meet strict safety and health regulations, including International Air Transport Association, Federal Aviation Administration (FAA), and International Electrotechnical Commission (IEC) guidelines, and ensure safe use in occupied cabins without interfering with critical systems [1].

Conclusion

Designing UV-C disinfection systems for aircraft involves integrating safety, efficiency, redundancy, and compliance to ensure effective pathogen protection. Evolving technology will shape their implementation and adoption in aviation.

REGULATORY AND SAFETY STANDARDS

The integration of UV-C disinfection systems in aircraft cabins is subject to rigorous regulatory oversight to ensure passenger safety and compliance with industry standards. This section outlines the key regulatory frameworks and safety standards governing the use of UV-C technology in aviation.

FAA Regulations

In the United States, ICAO and the FAA regulate the use of novel disinfection systems in aircraft.

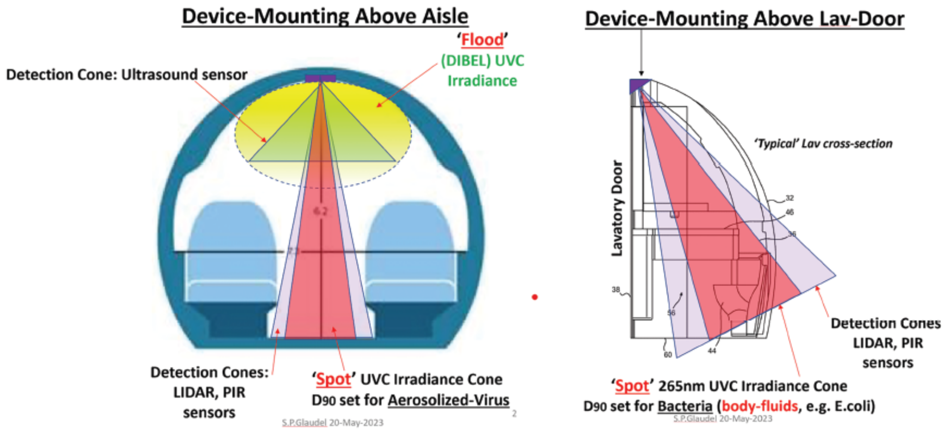

Figure 3. Examples of Engineering Control Systems *(Source: DeJohn et al. [4])*.

The FAA's regulations focus on ensuring that these systems do not interfere with the aircraft's safety or operational integrity. These regulations involve the following [1]:

- **Certification and Approval:** All aircraft systems require FAA certification, including tests for electromagnetic interference, structural integrity, system compatibility, and radiation effects on cabin materials like plastics and fabrics.
- **Operational Safety:** The FAA mandates safety features for aircraft systems, including automatic shut-offs, redundant controls, and crew guidelines, along with regular inspections to ensure safe operation.

Compliance and Certification for UV-C Systems

Compliance with regulatory standards is critical for implementing UV-C disinfection in commercial aircraft. The Project Specific Certification Plan (PSCP) outlines the steps to ensure the system meets FAA standards while maintaining airworthiness and safety. The process begins with the PSCP development and application for a supplemental-type certificate, which is granted after successful certification and compliance with FAA safety standards.

Key certification steps include the following:

- **Technical Standards Orders:** Ensures all components meet FAA criteria for reliability and safety in aircraft environments.
- **System Safety Analysis:** Conducts a failure hazard assessment to identify risks and ensure redundancies and fail-safes.
- **DO-160 Testing:** Verifies system performance under conditions like vibration, temperature changes, and electrical stress.
- **Flammability Testing:** Confirms components do not contribute to fire hazards.
- **Radiometric Validation:** Ensures UV-C irradiance levels stay within safe exposure limits.

Compliance is documented in the "Instructions for Continued Airworthiness, Responsibilities, Requirements, and Contents" which details maintenance procedures and standard operating procedures for safe and effective system use [22]. For new production aircraft, integrating UV-C systems during the design phase allows manufacturers to optimize placement and operation, with the system included in a type certificate, and certify compliance from the outset. This rigorous, phased process ensures UV-C systems align with all safety and regulatory standards.

IEC Standards

The IEC sets global safety standards for UV-C use, including aviation. IEC 62471:200 specifically addresses the photobiological safety of lamps and systems, such as the following [23]:

- **Photobiological Safety:** IEC 62471:200 defines UV-C hazard levels and sets exposure limits to ensure aircraft systems are safe for passengers and crew in occupied spaces.
- **System Design Compliance:** Aircraft UV-C systems must meet IEC standards for shielding, filters, and other protective measures to limit radiation exposure. IEC guidelines for testing and verification ensure systems operate within safe limits for passenger safety.

Occupational Safety and Health Administration (OSHA) Guidelines

For airline personnel, OSHA provides additional guidelines on UV-C exposure in the workplace. These guidelines are intended to protect maintenance workers, cleaning staff, and other personnel who may be exposed to UV-C radiation during aircraft servicing and include the following [1]:

- **Workplace Safety Standards:** OSHA recommends that airlines implement comprehensive training programs to educate employees about the risks associated with UV-C radiation and the proper use of personal protective equipment (PPE). OSHA also advises regular monitoring of UV-C exposure levels in work environments to ensure they remain within safe limits.

- **PPE:** OSHA guidelines suggest the use of PPE, such as UV-blocking eyewear and protective clothing, for workers who may be exposed to UV-C radiation during maintenance or disinfection procedures. These precautions help minimize the risk of acute injuries, such as photokeratitis or erythema, and protect workers from potential long-term health effects.

Future Regulatory Developments

As UV-C technology evolves, regulatory bodies are likely to update and refine their standards to reflect new research and emerging best practices. Future developments may include stricter guidelines on the use of far-UV-C light in occupied spaces, enhanced safety protocols for continuous disinfection, and new certification processes for innovative UV-C systems.

Regulatory agencies are closely monitoring ongoing research into the long-term effects of UV-C exposure, particularly with the newer far-UV-C technologies. This research will inform future regulatory updates and ensure that safety standards remain aligned with the latest scientific findings and technological advancements [1, 21, 13].

PROSPECTS AND INNOVATIONS

The integration of UV-C disinfection technology in the aviation industry is poised to evolve significantly as research advances and new innovations emerge. This section explores the prospects of UV-C technology in aircraft disinfection, focusing on potential innovations that could enhance its effectiveness, safety, and accessibility.

Advancements in Far-UV-C Technology

The electromagnetic spectrum is shown in Figure 4. Far-UV-C light, which operates in the 207–222-nm wavelength range, represents one of the most promising developments in UV-C technology

Unlike UV-A and UV-B light, far-UV-C is less penetrating—it can inactivate pathogens effectively without posing a significant risk to human skin and eyes (as shown in Figure 5). This makes far-UV-C particularly suitable for continuous use in occupied spaces like aircraft cabins.

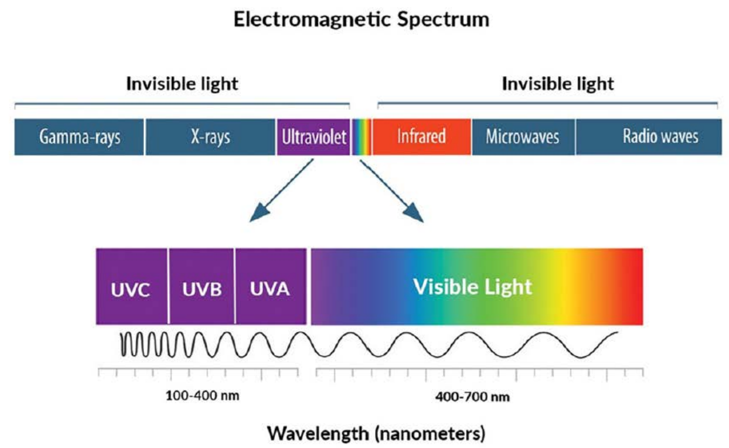

Figure 4. The Electromagnetic Spectrum *(Source: National Institute of Health [NIH] [24])*.

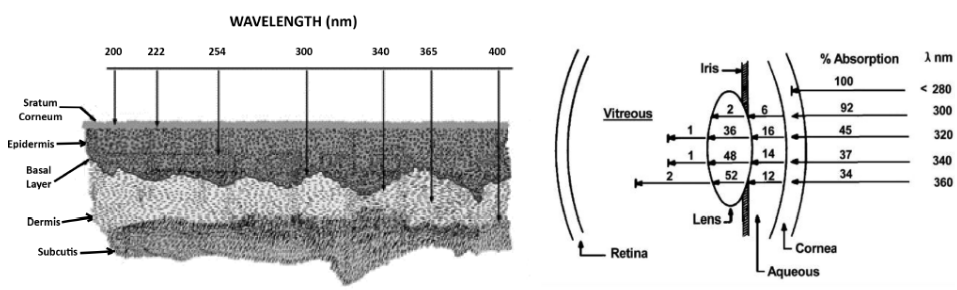

Figure 5. Ultraviolet Penetration of Skin and Eye *(Source: DeJohn et al. [4])*.

As the evidence around far-UV-C technology grows, it is becoming clearer how continuous disinfection could be integrated into everyday flight operations. At the same time, advancements in device miniaturization hint at targeted, portable solutions for high-contact surfaces. The following points illustrate how airlines could harness far-UV-C for both safer in-flight conditions and more versatile deployment options:

- **Increased Adoption and Safety:** With research supporting far-UV-C safety, airlines can adopt this technology for continuous in-flight disinfection. Integration into existing lighting and ventilation systems, along with smart sensors adjusting intensity based on occupancy, enhances real-time pathogen reduction and safety [1].
- **Miniaturization and Portability:** Advances may yield compact far-UV-C devices for targeted disinfection of aircraft touchpoints [1].

Innovations in UV-C LED Technology

The development of UV-C LEDs represents a significant innovation that could transform the use of UV-C disinfection in aviation. UV-C LEDs offer several advantages over traditional mercury-vapor lamps, including lower energy consumption, longer life spans, and the ability to produce light in specific wavelengths. These advantages include the following [1]:

> *The development of UV-C LEDs represents a significant innovation that could transform the use of UV-C disinfection in aviation.*

- **Energy Efficiency and Sustainability:** As UV-C LED technology advances, it is expected to become more energy efficient, reducing the operational costs associated with UV-C disinfection and making continuous disinfection more viable.
- **Customizable and Flexible Designs:** UV-C LEDs can be designed to emit light in precise wavelengths, allowing for the customization of disinfection systems based on specific needs. Different areas of the aircraft could be equipped with LEDs optimized for either air or surface disinfection. In addition, flexible LED arrays could also be developed, allowing for the installation of UV-C systems in previously inaccessible areas.

Development of Hybrid Disinfection Systems

The future of aircraft disinfection may lie in hybrid systems that combine UV-C technology with other disinfection methods to provide comprehensive protection against a wide range of pathogens. These systems include the following benefits [1]:

- **Combination With Chemical Disinfectants:** Hybrid systems utilizing UV-C light and chemical disinfectants could offer the best of both worlds, with UV-C providing continuous in-flight disinfection and chemicals offering a powerful adjunct for more stubborn pathogens.
- **Integration With Air Filtration Technologies:** UV-C systems can be integrated with advanced air filtration technologies, such as HEPA filters and electrostatic precipitators, to create a multilayered defense against airborne pathogens.

Regulatory Evolution and Standardization

As UV-C technology continues to develop, regulatory bodies are likely to evolve their standards to accommodate new innovations. This evolution will ensure that UV-C systems remain safe and effective as they become more widely used in the aviation industry. Such standards include the following [1]:

- **Harmonization of Global Standards:** The future may see greater harmonization of UV-C safety standards across different countries and regions, facilitating the global adoption of UV-C technology in aviation. This harmonization could also streamline the certification process for new UV-C systems, making it easier for airlines to implement cutting-edge technologies.

- **Adapting to Emerging Technologies:** As new UV-C technologies emerge, regulatory bodies will need to adapt their guidelines to address the unique challenges and opportunities these innovations present. This could include setting new exposure limits for far-UV-C light, establishing standards for Internet of Things-integrated systems, and developing guidelines for hybrid disinfection technologies [1].

LESSONS LEARNED AND FUTURE DIRECTIONS

The adoption of UV-C disinfection in aviation highlights the need for integration with existing systems, safety monitoring, and its role in a multilayered strategy. Airlines are advancing the use of UV-C technology, incorporating compact and cost-effective robotic solutions. These innovations highlight the potential to significantly enhance air travel safety, especially in addressing future health challenges.

> *The adoption of UV-C disinfection in aviation highlights the need for integration with existing systems, safety monitoring, and its role in a multilayered strategy.*

CONCLUSIONS

The future of UV-C disinfection in aviation is promising, with innovations in far-UV-C, LEDs, and hybrid systems enhancing safety and effectiveness. Supported by technological innovation, UV-C disinfection is poised to become key to aircraft hygiene and ensure safer travel [1, 4]. ■

REFERENCES

[1] Belland, K., D. Garcia, and C. DeJohn. "Safety and Effectiveness Assessment of Ultraviolet-C Disinfection in Aircraft Cabins." *Aerospace Medicine and Human Performance*, vol. 95, no. 3, pp. 147–57, March 2024.

[2] Rafferty, A., K. Bofkin, W. Hughes, S. Souter, et al. "Does 2×2 Airplane Passenger Contact Tracing for Infectious Respiratory Pathogens Work? A Systematic Review of the Evidence." *PLOS ONE*, vol. 18, no. 2, e0264294, 2 February 2023.

[3] Allen, G. "A Risk vs. Benefit Analysis UV-C Advanced Aircraft Disinfection." *Aerospace Medicine and Human Performance*, in press.

[4] DeJohn, C., K. Belland, D. Garcia. "Methods of Aircraft Disinfection to Reduce Airborne Infectious Disease Transmission." *Aerospace Medicine and Human Performance*, vol. 95, no. 12, pp. 934–936, December 2024.

[5] Reed, N. G. "The History of Ultraviolet Germicidal Irradiation for Air Disinfection." *Public Health Rep.*, vol. 125, no. 1, pp. 15–27, 2010.

[6] Brenner, D. "Far-UVC Light at 222 nm is Showing Significant Potential to Safely and Efficiently Inactivate Airborne Pathogens in Occupied Indoor Locations." *Photochem. Photobiol.*, vol. 990, no. 3, pp. 1047–1050, 4 November 2022.

[7] Blazejewski, C., M. Guerry, P. Sebastien, A. Durocher, and S. Nseir. "New Methods to Clean ICU Rooms." *Infect. Disord. Drug Targets*, vol. 11, no. 4, pp. 365–75, August 2011.

[8] Ramos, C. C. R., J. L. A. Roque, D. B. Sarmiento, L. E. G. Suarez, J. T. P. Sunio, K. I. B. Tabungar, et al. "Use of Ultraviolet-C in Environmental Sterilization in Hospitals: A Systematic Review on Efficacy and Safety." *Int. J. Health Sci. (Qassim)*, vol. 14, no. 6, pp. 52–65, 2020.

[9] Welch, D., M. Buonanno, V. Grilj, I. Shuryak, C. Crickmore, et al. "Far-UVC Light: A New Tool to Control the Spread of Airborne-Mediated Microbial Diseases." *Sci. Rep.*, vol. 8, no. 1, pp. 2752–2759, 9 February 2018.

[10] Narita, K., K. Asano, K. Naito, H. Ohashi, M. Sasaki, Y. Morimoto, et al. "Ultraviolet C Light With Wavelength of 222 nm Inactivates a Wide Spectrum of Microbial Pathogens." *Journal of Hospital Infection*, vol. 105, no. 3, pp. 459–467, 1 July 2020.

[11] Wang, X. V., and L. Wang. "A Literature Survey of the Robotic Technologies During the COVID-19 Pandemic." *Journal of Manufacturing Systems*, vol. 60, pp. 823–836, 1 July 2021.

[12] Allen, G., K. Benner, and W. Bahnfleth. "Inactivation of Pathogens in Air Using Ultraviolet Direct Irradiation Below Exposure Limits." *J. Res. Natl. Inst. Stand. Technol.*, vol. 126, 1 March 2022.

[13] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ASHRAE Standard 241: "Control of Infectious Aerosols." https://www.ashrae.org/technical-resources/bookstore/ashrae-standard-241-control-of-infectious-aerosols, 2023.

[14] Wang, F., R. You, T. Zhang, and Q. Chen. "Recent Progress on Studies of Airborne Infectious Disease Transmission, Air Quality, and Thermal Comfort in the Airliner Cabin Air Environment." *Indoor Air*, vol. 32, no. 4, e13032, 2022.

[15] Blatchley, E., D. Brenner, H. Claus, T. Cowan, K. Linden, Y. Liu, et al. "Far UV-C Radiation: An Emerging Tool for Pandemic Control." *Critical Reviews in Environmental Science and Technology*, vol. 53, no. 6, pp. 733–53, 19 March 2023.

[16] Biasin, M., A. Bianco, G. Pareschi, A. Cavalleri, C. Cavatorta, C. Fenizia, et al. "UV-C Irradiation Is Highly Effective in Inactivating SARS-CoV-2 Replication." *Sci. Rep.*, vol. 11, no. 1, p. 6260, 18 March 2021.

[17] Barnard, I., E. Eadie, and K. Wood. "Further Evidence That Far-UVC for Disinfection Is Unlikely

to Cause Erythema or Pre-Mutagenic DNA Lesions in Skin." *Photodermatology, Photoimmunology & Photomedicine*, vol. 36, no. 6, pp. 476–477, November 2020.

[18] Blatchley, E. R., D. Brenner, H. Claus, T. E. Cowan, and D. Sliney. "Far UV-C Radiation: Current State-of Knowledge." The International Ultraviolet Association (IUVA), https://iuva.org/resources/covid-19/Far%20UV-C%20Radiation-%20Current%20State-of%20Knowledge.pdf, 2021.

[19] Allen, J. "Ultraviolet Radiation: How it Affects Life on Earth." NASA Earth Observatory, Ultraviolet Radiation: How It Affects Life on Earth, 6 September 2001.

[20] Belland, K., D. Garcia, C. DeJohn, G. R. Allen, W. D. Mills, and S. P. Glaudel. "Safety and Effectiveness Assessment of Ultraviolet-C Disinfection in Aircraft Cabins." *Aerospace Medical & Human Performance*, vol. 95, no. 3, p. 148, 1 March 2024.

[21] Yang, J. H., U. I. Wu, H. M. Tai, and W. H. S heng. "Effectiveness of an Ultraviolet-C Disinfection System for Reduction of Healthcare-Associated Pathogens." *Journal of Microbiology, Immunology and Infection*, vol. 52, no. 3, pp. 487–493, 1 June 2019.

[22] FAA. "Instructions for Continued Airworthiness Responsibilities, Requirements, and Contents." FAA Order 8110.54A, https://www.faa.gov/documentLibrary/media/Order/FAA_Order_8110.54A.pdf, accessed on 24 February 2025.

[23] International Electrotechnical Commission. "Photobiological Safety of Lamps and Lamp Systems." IEC 62471:200, https://www.iecee.org/certification/iec-standards/iec-624712006, accessed on 25 February 2025.

[24] NIH. "Protecting Your Eyes From the Sun's UV Light." National Eye Institute, https://www.nei.nih.gov/about/news-and-events/news/protecting-your-eyes-suns-uv-light, 5 July 2022.

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