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# Preliminary Design Framework for CHARR-Based Active Air Disinfection Systems in Military Facilities

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## Abstract

**Purpose:** This study develops a preliminary design framework for active air disinfection systems in military facilities, using CHARR as a reference architecture rather than as a field-validated product. It addresses the need for safer, continuous indoor environmental management in barracks, medical spaces, command rooms, training facilities, and enclosed naval spaces. **Research Design & Data:** The study applies a design science and evidence-mapping approach. It synthesizes peer-reviewed literature, technical reports, laboratory and chamber test summaries, hospital application materials, safety documents, product specifications, and military facility requirements. Evidence was interpreted as design-relevant support, not as direct proof of military effectiveness. **Research Results:** The framework identifies five core modules: catalytic reaction, airflow and HVAC integration, filtration and deodorization, sensing and control, and monitoring and management. It further proposes five facility-specific application models and a staged deployment pathway from local pilot installation to sensor integration, HVAC linkage, local dashboard management, and approved central reporting. Safety monitoring should include $H_2O_2$, ozone, VOCs, $CO_2$, PM, temperature, humidity, device status, alarms, and maintenance records. **Conclusion:** CHARR/NCC-type systems may support military indoor air management when treated as part of an integrated environmental-control platform. Future work should conduct controlled field demonstrations under military conditions before large-scale deployment and policy evaluation.

**Keywords :** Active Air Disinfection, Military Facilities, CHARR Reference Architecture, Indoor Air Quality, Safety Monitoring

**JEL Classification Code** : H56, I18, Q53, Q55, O32

## 1. Introduction
[1]

### 1.1. Background

Indoor air quality has become an increasingly important issue in military facilities because military personnel often live, train, work, and operate in enclosed or semi-enclosed environments for extended periods. Barracks, recruit training centers, command-and-control rooms, medical facilities, naval vessels, and other operational spaces are

characterized by high occupancy density, shared air, repeated surface contact, and limited flexibility in ventilation and space separation. Previous studies have shown that building characteristics and ventilation design can influence respiratory infection risk in military training environments. Brundage et al. (1988) reported that trainees housed in tightly constructed modern barracks with closed ventilation systems had higher rates of febrile acute respiratory disease, supporting the hypothesis that closed ventilation and building tightness may increase respiratory-transmitted infection risk among congregated occupants.

White et al. (2011) also examined ventilation design, room occupancy, barracks type, and acute respiratory infection rates in Army Basic Combat Training barracks. In Korea, Kim et al. (2007) evaluated indoor air quality in R.O.K. Army barracks and provided domestic evidence that military barracks require systematic indoor air quality management. In the Korean context, military indoor air management is also related to institutional facility management and regulatory compliance. Korea has a general legal framework for indoor air quality management in multi-use facilities, and the Indoor Air Quality Control Act requires facility managers to maintain indoor air quality according to prescribed standards.

Although military facilities have operational characteristics that differ from ordinary civilian facilities, this regulatory background indicates that indoor air quality should be managed through measurable indicators, maintenance procedures, and documented control practices rather than through ad hoc responses. In addition, the Ministry of National Defense has established a separate military indoor air quality management directive, which confirms that indoor air quality in military spaces is an institutional management issue rather than merely a building-comfort issue. Therefore, active air disinfection systems for Korean military facilities should be discussed within the broader context of barracks modernization, facility safety, environmental health, and continuous operational readiness. These studies suggest that indoor air management in military facilities should be understood not merely as a comfort issue but also as an environmental health and operational-readiness issue.

Conventional indoor air management in military and institutional facilities has generally relied on ventilation, filtration, periodic surface disinfection, and portable air-cleaning devices. These measures remain essential, but they have limitations when applied to dense and continuously occupied environments. Ventilation may be constrained by outdoor conditions, building design, energy demand, seasonal conditions, or operational security requirements. Filtration-based systems mainly remove particles that pass through the filter or device, while periodic surface disinfection is episodic and may not prevent rapid recontamination in high-traffic spaces. Recent standards and public health guidance increasingly frame indoor infection-risk reduction as an integrated engineering problem involving ventilation, filtration, air cleaning, and operational maintenance. ASHRAE Standard 241 addresses control of infectious aerosols in buildings, while CDC/NIOSH guidance explains germicidal ultraviolet as a technology for inactivating microorganisms in air or on surfaces when properly applied.

Active air disinfection systems have been discussed as one possible component of such an integrated environmental-control strategy. Unlike passive air-cleaning approaches that primarily rely on particle capture, active air disinfection technologies aim to reduce biological contaminants through physical or chemical inactivation mechanisms. These systems may include ultraviolet germicidal irradiation, photocatalytic oxidation, catalytic conversion, hydrogen peroxide-based treatment, plasma-based technologies, ionization-based systems, or hybrid mechanisms. Luo and Zhong (2021) reviewed in-duct ultraviolet germicidal irradiation for airborne bioaerosol disinfection in HVAC ducts and emphasized its applicability where full shutdown of air recirculation is not feasible. Nardell (2021) also discussed germicidal ultraviolet air disinfection as a long-established method for airborne infection control, particularly in occupied indoor spaces when properly designed and maintained. These studies support the view that active air disinfection should be evaluated as part of building-level environmental control rather than as a stand-alone device.

In this study, CHARR is used as a reference architecture for developing a preliminary design framework for military active air disinfection systems. CHARR, defined as a Catalytic Honeycomb Air Oxidation–Reduction Reactor, is conceptualized as a catalytic air-treatment platform derived from NCC-type photocatalytic conversion technology. The broader scientific basis for this type of catalytic air-treatment concept can be linked to photocatalytic oxidation research. Zhao and Yang (2003) reviewed photocatalytic oxidation for indoor air purification and showed that PCO has been studied for the destruction of indoor VOCs, with performance affected by moisture, light intensity, initial contaminant concentration, and reactor design. Huang et al. (2016) reviewed photocatalytic oxidation for indoor VOC and formaldehyde removal and discussed key influencing factors such as temperature, relative humidity, photocatalyst deactivation, and reactivation. Yu and Kim (2013) also reviewed PCO techniques for reducing indoor air pollutants

and maintaining indoor environmental quality. These studies indicate that catalytic or photocatalytic modules should be treated as engineered components whose performance depends on reactor configuration, airflow, pollutant load, and environmental conditions.

At the same time, active air-cleaning technologies require careful safety evaluation. Photocatalytic oxidation and ultraviolet-based air-cleaning systems may generate chemical by-products under certain conditions. Link et al. (2024) quantified by-product formation from portable air cleaners using a proposed standard test method, emphasizing that air-cleaning technologies should be evaluated not only for removal efficiency but also for by-product formation. Hydrogen peroxide-based disinfection also requires careful interpretation. Poppendieck et al. (2021) reviewed vaporous hydrogen peroxide as an indoor disinfectant and highlighted both its disinfection potential and its interaction with indoor materials and associated emissions of organic compounds. Taneja et al. (2011) assessed hydrogen peroxide vapor for decontaminating air-conditioning ducts and rooms, while Wright et al. (2024) reported that dry hydrogen peroxide has potential to reduce air and surface microbial bioburden in occupied patient rooms under standard ventilation conditions. These studies support the need to incorporate $H_2O_2$, ozone, VOCs, by-products, and device-status monitoring into any preliminary design framework for occupied military spaces.

Existing laboratory, chamber, hospital, and safety materials suggest that CHARR/NCC-type systems may provide design-relevant evidence for air and surface environmental management. However, these materials do not by themselves establish direct effectiveness in military environments. Military facilities differ from hospitals, laboratories, public transportation settings, and civilian buildings in occupancy patterns, mission requirements, spatial layouts, maintenance systems, security constraints, and operational risk tolerance. Therefore, direct transfer of prior performance claims to military facilities would be inappropriate without a separate design and validation framework. What is needed first is not an assertion of universal effectiveness, but a preliminary design framework that translates the technical characteristics of active air disinfection systems into military facility requirements.

Accordingly, this study aims to develop a preliminary design framework for active air disinfection systems in military facilities, using CHARR as a reference architecture. The study does not conduct a new field experiment and does not claim to validate clinical, epidemiological, or operational outcomes in military settings. Instead, it synthesizes existing technical reports, laboratory test summaries, hospital application materials, safety documents, product specifications, military facility requirements, and relevant peer-reviewed literature to propose a structured system architecture and application model for future field demonstration.

The proposed framework focuses on five design dimensions: the catalytic reaction module, airflow and HVAC integration, filtration and deodorization, sensing and control, and monitoring or management functions. It also considers military-specific deployment models, including barracks, medical facilities, command-and-control spaces, training facilities, and naval or enclosed operational spaces. In addition, the study addresses safety and operational design issues such as ozone, low-level $H_2O_2$, VOCs, noise, maintenance, redundancy, security restrictions, and staged integration with local or centralized monitoring systems.

The contribution of this study is threefold. First, it reframes active air disinfection in military facilities as a system architecture problem rather than a stand-alone device issue. Second, it organizes existing technical, safety, and scholarly evidence into military-relevant design requirements while explicitly avoiding direct claims of field-proven effectiveness. Third, it proposes facility-specific application models and staged deployment criteria that can support future pilot testing, field demonstration, and policy-level evaluation. Through this approach, the study provides a technical and operational foundation for developing military indoor air management systems that integrate infection-risk reduction, environmental quality improvement, facility modernization, and continuous operational management.

## 2. Literature Review

### 2.1. Indoor Air Quality and Infection Risk in High-Occupancy Military Facilities

Military facilities differ from ordinary residential, commercial, and institutional buildings because they are designed to support collective living, training, command, medical care, and operational readiness. Barracks, recruit training centers, command-and-control rooms, medical facilities, shipboard spaces, and enclosed training environments often involve high occupancy density, prolonged indoor stay, repeated interpersonal contact, and shared air. These characteristics make military environments particularly vulnerable to indoor air quality deterioration and respiratory infection transmission.

Although military-specific indoor air studies remain limited, broader research on ventilation and airborne infection

provides a strong theoretical basis for considering military indoor air management as both an environmental health issue and an operational issue. Li et al. (2007) conducted a multidisciplinary systematic review and concluded that ventilation, air movement, and airflow patterns in buildings are associated with the transmission and spread of airborne infectious diseases. Sundell et al. (2011) also reviewed the relationship between ventilation rates and health outcomes, suggesting that lower ventilation rates may be associated with increased respiratory symptoms and other adverse health effects in indoor environments. These findings are highly relevant to military barracks and training facilities, where personnel remain indoors for extended periods and share air in high-density conditions.

Studies in shared residential or dormitory environments provide additional evidence relevant to military living spaces. Sun et al. (2011) found that students in crowded dormitories with low outdoor-airflow rates had more common colds, supporting the role of ventilation in reducing respiratory infection risk in shared sleeping environments. Zhu et al. (2020) examined ventilation and laboratory-confirmed acute respiratory infection rates in college residence halls, showing that residence-hall ventilation can be meaningfully linked to respiratory infection risk. While college dormitories are not identical to military barracks, they provide useful analogues because both involve shared sleeping areas, dense occupancy, and prolonged indoor residence.

Accordingly, indoor air quality in military facilities should be understood not only in relation to comfort, odor, or pollutant concentration, but also in relation to infection-risk reduction, manpower availability, training continuity, and operational readiness. This supports the need for a system-level approach in which air treatment, surface contamination control, monitoring, maintenance, and operational management are considered together rather than separately.

For Korean military facilities, this issue is particularly important because barracks are not merely dormitory-like residential spaces but institutional living environments connected to training continuity, personnel health, and unit readiness. Barracks modernization has improved the physical quality of military living spaces, but modernization also requires systematic management of ventilation, humidity, particulate matter, carbon dioxide, odors, mold-related risk, and infection-reduction measures. The Korean military indoor air quality management framework also implies that ventilation, air cleaning, measurement, record keeping, and facility improvement should be treated as part of routine facility management. Therefore, a military active air disinfection framework should be designed not as a replacement for ventilation or cleaning but as an additional environmental-control layer that can be integrated into existing barracks and military facility management systems.

## 2.2. Conventional Approaches to Indoor Air Management

Conventional indoor air management strategies generally include ventilation, filtration, periodic surface cleaning, and localized air-purification devices. Ventilation is one of the most fundamental engineering controls because it dilutes indoor contaminants and reduces the accumulation of exhaled aerosols, carbon dioxide, volatile organic compounds, odors, and other airborne substances. However, ventilation performance depends on outdoor air supply, air distribution, room geometry, occupancy, and operating conditions.

Qian et al. (2010) showed that high ventilation rates can reduce airborne cross-infection risk in hospital wards and isolation rooms, suggesting that ventilation can function as an infection-control measure when properly designed and operated. Gao et al. (2016) further modeled building ventilation as a disease-intervention strategy in dense indoor contact networks and concluded that increasing building ventilation can be an effective measure for reducing airborne disease spread. These findings support the inclusion of ventilation and airflow management in any military indoor air control framework.

Filtration is another core strategy. Azimi and Stephens (2013) modeled the effect of HVAC filtration on infectious airborne disease transmission risk and operational cost, showing that recirculating HVAC filters can contribute to risk reduction under appropriate conditions. Fisk (2013) reviewed health benefits of particle filtration and concluded that filtration may reduce indoor exposure to particles and produce health benefits, although the magnitude depends on system design, exposure conditions, and filter performance. For military facilities, this means filtration should be treated as one layer of control, not as a complete solution.

Periodic surface disinfection and portable air-cleaning devices can supplement building-level controls, but they have limitations in dense and continuously occupied environments. Surface disinfection is episodic and may be followed by rapid recontamination, while portable devices depend on placement, airflow patterns, maintenance, and user compliance. Therefore, military facilities require a more integrated approach that combines ventilation, filtration, active disinfection, environmental sensing, and maintenance protocols.

## 2.3. Active Air Disinfection and Continuous Environmental Treatment

Active air disinfection technologies aim to reduce biological contaminants by inactivating or decomposing microorganisms rather than merely capturing them. Such technologies include ultraviolet germicidal irradiation, photocatalytic oxidation, catalytic conversion, hydrogen peroxide-based treatment, plasma-based systems, ionization-based systems, and hybrid approaches. Their effectiveness depends on mechanism, device design, airflow conditions, exposure time, target microorganisms, room geometry, and environmental conditions.

Recent research on airborne infection has strengthened the case for building-level environmental controls. Morawska and Milton (2020) argued that airborne transmission of COVID-19 required greater attention and that control measures should address airborne routes. Morawska et al. (2021) further called for a paradigm shift in how buildings are designed and operated to combat indoor respiratory infection. These studies support the view that indoor air management should not be treated as an optional comfort function, but as part of infection-risk governance in occupied buildings.

For military facilities, this argument is especially relevant because many spaces are continuously occupied and cannot easily be vacated for episodic disinfection. Barracks, command-and-control rooms, medical spaces, and shipboard compartments require technologies that can operate safely under occupied conditions. Therefore, active air disinfection should be considered only within a broader environmental-control strategy that includes airflow design, safety monitoring, maintenance, and field validation.

## 2.4. Ultraviolet Germicidal Irradiation and HVAC-Integrated Air Disinfection

Ultraviolet germicidal irradiation has been studied as an air-disinfection method for decades and is particularly relevant to HVAC-integrated or upper-room applications. Escombe et al. (2009) demonstrated that upper-room ultraviolet light and negative air ionization reduced airborne tuberculosis transmission in a controlled ward-air model, indicating that UV-based air disinfection can reduce airborne infection risk under appropriate conditions. Mphaphlele et al. (2015) later conducted a controlled trial of upper-room germicidal ultraviolet air disinfection and found that upper-room UVGI with air mixing was highly effective in reducing tuberculosis transmission under hospital conditions.

In addition to upper-room systems, HVAC or duct-integrated air disinfection is relevant to military facilities because barracks, medical facilities, command centers, and training spaces often rely on building-level air circulation. Although UVGI is not identical to CHARR/NCC-type catalytic treatment, the UVGI literature is important because it demonstrates that active air disinfection must be evaluated as an engineering system involving airflow, exposure, dose, mixing, and maintenance. This provides a useful precedent for treating CHARR-based active disinfection as a system architecture problem rather than as a stand-alone device issue.

## 2.5. Monitoring Indicators: $CO_2$, VOCs, and Occupant-Related Air Quality

A system-level indoor air framework requires measurable indicators. $CO_2$ is commonly used as an occupancy and ventilation-related indicator, particularly in densely occupied spaces. Persily and de Jonge (2017) provided updated carbon dioxide generation rates for building occupants, supporting the use of $CO_2$ as a practical indicator for interpreting occupancy and ventilation conditions. In military settings, $CO_2$ monitoring can be particularly useful in barracks, classrooms, and command rooms where occupancy varies over time.

Indoor air quality may also affect human performance. Allen et al. (2016) conducted a controlled exposure study and found associations between cognitive function scores and carbon dioxide, ventilation, and volatile organic compound exposures in office workers. Although the study was not conducted in military facilities, it is relevant because command-and-control rooms, training spaces, and operational centers require sustained cognitive performance under indoor conditions. This supports the inclusion of $CO_2$ and VOC monitoring in military indoor air management systems.

Therefore, monitoring in military active air disinfection systems should not be limited to device status. It should include environmental quality indicators such as $CO_2$, PM, VOCs, temperature, humidity, and, where applicable, chemical by-products associated with active treatment.

## 2.6. Photocatalytic Oxidation and Catalytic Air Treatment

Photocatalytic oxidation provides an important scientific background for catalytic active air-treatment systems. Mo et al. (2009) reviewed photocatalytic purification of volatile organic compounds in indoor air and described photocatalytic oxidation as a promising method for indoor VOC removal. The review emphasized that performance

depends on photocatalyst preparation, coating, reactor design, airflow, pollutant concentration, intermediates, and reaction conditions. Bui et al. (2021) also reviewed photocatalytic materials for indoor air purification systems and summarized recent progress in photocatalyst development for degrading gas-phase air pollutants.

These studies are directly relevant to the catalytic reaction module proposed in this study. They suggest that catalytic or photocatalytic air-treatment systems should be evaluated as engineered reactors rather than as generic air purifiers. In other words, performance depends on the interaction among catalyst structure, light source, airflow, pollutant load, humidity, and residence time. This supports the decision to treat CHARR as a reference architecture for system design rather than as a field-validated solution.

## 2.7. By-Product Formation and Safety Concerns in Active Air Treatment

Active air treatment technologies may generate unintended chemical by-products under some operating conditions. Zhong and Haghighat (2018) modeled by-products from photocatalytic oxidation indoor air purifiers and examined how operational variables such as concentration, relative humidity, airflow, and irradiance affect formaldehyde and acetaldehyde formation. This is important because catalytic or photocatalytic systems can reduce some pollutants while potentially producing secondary products that require monitoring.

This safety issue is particularly important for military facilities because systems may operate in occupied sleeping quarters, command rooms, medical spaces, or enclosed shipboard compartments. Therefore, any CHARR-based reference architecture should include monitoring for $H_2O_2$, ozone, VOCs, aldehydes, and other by-products where applicable. Safety monitoring should not be added after deployment; it should be built into commissioning, operation, and field demonstration from the beginning.

## 2.8. System Architecture Perspective for Military Indoor Air Management

The literature reviewed above supports a system architecture perspective. Ventilation studies show that airflow and air-exchange conditions influence infection risk. Filtration studies show that HVAC-linked particle removal can contribute to risk reduction. UVGI studies show that active air disinfection depends on air mixing, dose, and installation design. Photocatalytic oxidation studies show that catalytic air treatment depends on reactor configuration and operating conditions. By-product studies show that active technologies require safety monitoring.

For military application, active air disinfection should therefore not be considered only as a device-level intervention. Military facilities require a system architecture that links treatment mechanisms, airflow, filtration, sensing, safety monitoring, maintenance, and operational reporting. A device may have microbial-reduction potential under controlled conditions, but military deployment requires additional consideration of space volume, occupancy density, airflow pattern, operating schedule, equipment durability, maintenance capacity, safety assurance, cybersecurity, and command-level approval.

Accordingly, a military design framework should include not only the treatment module but also airflow integration, filtration or deodorization, sensor-based monitoring, safety verification, and staged deployment. This broader design approach reduces the risk of overclaiming technology performance and provides a more practical foundation for future field demonstration.

## 2.9. CHARR as a Reference Architecture for Active Air Disinfection

In this study, CHARR is used as a reference architecture for developing a preliminary design framework for active air disinfection systems in military facilities. CHARR, defined as a Catalytic Honeycomb Air Oxidation–Reduction Reactor, is conceptualized as a catalytic air-treatment platform derived from NCC-type photocatalytic conversion technology. Existing technical materials describe NCC technology as using a catalytic cell and ultraviolet light to generate low-level oxidizing species from ambient air and moisture. The Duct Station technical material describes NCC as a system using a 254 nm UVx lamp and a specially treated catalytic cell to generate oxidizing ions, including $H_2O_2$-related species, with intended effects on viruses, bacteria, mold, ethylene gas, odors, and airborne contaminants.

From a design perspective, the relevance of CHARR/NCC-type technology lies in its potential to support both air and surface environmental management. However, the peer-reviewed literature on ventilation, UVGI, filtration, and photocatalytic oxidation indicates that such technologies should be evaluated through design variables rather than assumed performance. CHARR should therefore be treated as a reference architecture rather than as a field-validated military solution.

This distinction is important. Laboratory or hospital testing may provide preliminary evidence for system design, but it

does not automatically establish effectiveness in barracks, ships, command rooms, or training facilities. Military deployment requires independent field demonstration under military-specific operating conditions.

### 2.10. Evidence from Technical Reports and Controlled Test Materials

In addition to peer-reviewed literature, this study considers technical reports, controlled chamber studies, safety summaries, and product specifications related to CHARR/NCC-type systems. These materials provide design-relevant information on catalytic reaction cells, UVx lamps, airflow capacity, microbial reduction under controlled conditions, surface microbial-burden reduction, $H_2O_2$ concentration, ozone non-detection, and HVAC integration.

However, such technical materials should be interpreted cautiously. They are useful for defining design assumptions, system components, measurement variables, and field-demonstration requirements, but they should not be treated as independent proof of military-field effectiveness. This distinction is consistent with the broader literature reviewed above, which emphasizes that air disinfection performance depends on operating context, airflow, exposure time, environmental conditions, and safety monitoring.

Therefore, in this study, technical reports are used as supplementary design evidence, while the main scholarly foundation is drawn from peer-reviewed studies on ventilation, filtration, UVGI, photocatalytic oxidation, $CO_2$/VOC monitoring, and by-product formation.

### 2.11. Design Gap and Need for a Military-Specific Framework

The reviewed literature suggests that active air disinfection technologies may have relevance for air and surface management in dense indoor environments, but it also reveals a clear design gap. Existing studies are largely based on hospitals, offices, college dormitories, experimental chambers, or general building environments. Military facilities have distinct requirements that are not fully addressed by these prior settings, including high-density collective living, mission-critical occupancy, barracks modernization, shipboard constraints, command-space continuity, maintenance limitations, cybersecurity restrictions, and the need for standardized operation across multiple facility types.

Therefore, a military-specific design framework is required. Such a framework should translate the general evidence on ventilation, filtration, air disinfection, catalytic treatment, monitoring, and safety into operational design requirements for barracks, medical spaces, command-and-control rooms, training facilities, and naval or enclosed spaces. The purpose of the present study is to develop such a framework by synthesizing peer-reviewed literature, technical reports, safety documentation, product specifications, and military facility requirements. This approach provides a bridge between general active air disinfection technology and practical military indoor air management.

## 3. Research Methods

### 3.1. Research Design

This study adopts a preliminary design-framework research approach to develop a military-specific application model for active air disinfection systems. The purpose of the study is not to conduct a new laboratory experiment or field trial, nor to validate the direct effectiveness of any specific technology in military environments. Rather, the study synthesizes existing technical reports, laboratory test summaries, safety documents, product specifications, and military facility requirements into a structured preliminary design framework.

Methodologically, the study is grounded in design science research. Design science research is appropriate when the objective is to develop and justify an artifact, model, method, architecture, or design principle intended to solve a practical problem. March and Smith (1995) distinguished design-oriented research from explanatory natural science research by emphasizing the activities of building and evaluating artifacts. Hevner et al. (2004) further argued that design science research should produce purposeful artifacts while maintaining relevance to real-world problems and rigor through connection to an existing knowledge base. Peffers et al. (2007) proposed a design science research methodology consisting of problem identification, objective definition, design and development, demonstration, evaluation, and communication.

The present study follows this logic by treating the proposed framework as a preliminary design artifact rather than as an experimentally validated technology. CHARR, defined as a Catalytic Honeycomb Air Oxidation–Reduction Reactor, is used as a reference architecture for examining how catalytic active air disinfection systems could be configured for military facilities. Following Gregor and Hevner (2013), the contribution of this study is positioned as an applied design contribution that translates prior evidence and technical knowledge into a structured architecture for a specific

application domain. Baskerville et al. (2018) emphasized that design science research can contribute through artifacts, theories, or both; in this study, the main contribution is a preliminary system architecture and deployment framework.

Because military facilities differ from hospitals, laboratories, and civilian buildings in occupancy patterns, mission continuity, maintenance conditions, facility layouts, and security constraints, this study focuses on how an active air disinfection system should be configured, monitored, and evaluated before military deployment. Accordingly, the proposed framework should be understood as a preliminary design model for future pilot testing, field demonstration, and operational evaluation, rather than as a completed validation model.

### 3.2. Data and Source Materials

The source materials used in this study were selected from four categories: technical system documents, laboratory and chamber test reports, hospital or healthcare application reports, and safety or conformity documents. These materials were reviewed to identify operating principles, design parameters, safety constraints, monitoring requirements, and deployment implications relevant to active air disinfection systems in military facilities.

The source review followed the logic of scoping and evidence-mapping approaches. Arksey and O'Malley (2005) proposed scoping studies as a way to map key concepts, evidence types, and gaps in a research area. Levac et al. (2010) later refined this approach by emphasizing clarity of purpose, iterative study selection, and meaningful synthesis. Tricco et al. (2018) further developed reporting guidance for scoping reviews through the PRISMA-ScR checklist. Although the present study is not a formal scoping review, these methodological principles informed the organization of heterogeneous evidence into design-relevant categories.

The first category consisted of technical system materials describing NCC or CHARR-related mechanisms, duct-type system configuration, airflow capacity, catalytic cell structure, UVx lamp operation, and intended treatment targets such as microorganisms, odors, VOCs, ethylene gas, and airborne contaminants. These materials were used to define the reference architecture and identify major system components.

The second category consisted of laboratory and chamber test reports. These included controlled tests on airborne microorganisms, surface microbial burden, and viral inactivation. These materials were not treated as direct evidence of military-field effectiveness. Instead, they were used as design-relevant evidence for identifying airflow, exposure-time, microbial-reduction, and monitoring considerations.

The third category included hospital and healthcare application reports. These materials were used to examine how continuous air and surface treatment systems have been applied in occupied healthcare spaces. Because healthcare facilities differ from military facilities, these reports were interpreted only as operational analogues for continuous occupied-space use, surface microbial-burden management, and integration with existing cleaning protocols.

The fourth category consisted of safety and conformity documents. These included materials related to $H_2O_2$ concentration, ozone generation, conformity declarations, medical-device classification, and occupied-space use. These documents were used to derive safety-related design requirements, including $H_2O_2$ monitoring, ozone monitoring, by-product assessment, and commissioning procedures.

### 3.3. Selection Criteria

Source materials were included when they met at least one of the following criteria. First, the material described the operating principle, system structure, or deployment configuration of NCC/CHARR-type photocatalytic conversion or catalytic air-treatment technology. Second, the material provided laboratory, chamber, or field-oriented evidence related to air microbial reduction, surface microbial-burden reduction, viral inactivation, odor or VOC control, or environmental treatment. Third, the material provided safety-related information on $H_2O_2$, ozone, by-products, occupied-space use, or conformity with technical standards. Fourth, the material was relevant to system deployment in spaces analogous to military facilities, such as hospitals, public transportation, HVAC-connected buildings, or high-occupancy indoor environments.

Materials were excluded when they were purely promotional, lacked identifiable technical content, did not describe test conditions or system configuration, or were unrelated to indoor air disinfection, surface decontamination, HVAC integration, or environmental safety. When a document contained both promotional and technical elements, only technical descriptions, test parameters, reported outcomes, safety information, and design-relevant implications were used.

The selection process was designed to support transparent evidence mapping rather than quantitative effect estimation. Webster and Watson (2002) emphasized that a strong literature review should organize prior work conceptually rather than merely list sources. In this study, source

materials were therefore organized according to their design relevance: technical mechanism, air-treatment evidence, surface-management evidence, safety evidence, HVAC integration, monitoring, and field-demonstration implications.

Because some materials were manufacturer-associated reports or proprietary summaries, their findings were interpreted cautiously. They were not used as conclusive proof of effectiveness. Instead, they were used to support the construction of a preliminary design framework and to identify variables that should be tested in future independent field demonstrations.

## 3.4. Analytical Procedure

The analysis proceeded in six stages.
First, the technical and test materials were reviewed to identify recurring system components, including catalytic reaction cells, UVx or UV-C light sources, airflow modules, filters, ducts, sensors, controllers, and monitoring functions. These components were organized into a preliminary active air disinfection system architecture.

Second, the evidence was classified according to functional relevance. Airborne microbial reduction evidence was used to inform air-treatment design. Surface microbial-burden evidence was used to support air-plus-surface management logic. $H_2O_2$ and ozone data were used to define safety-monitoring requirements. HVAC-related documents were used to identify duct integration, airflow, and facility-level deployment considerations.

Third, the evidence was translated into military design requirements. Direct performance transfer was avoided because military spaces differ from hospitals, laboratories, and public transportation environments. Each finding was therefore interpreted as a design implication rather than as proof of equivalent performance in military facilities. This step follows the logic of realist synthesis, which examines how evidence may work differently across contexts. Pawson et al. (2005) argued that complex interventions should be understood in terms of context, mechanism, and outcome rather than through simple universal claims. Rycroft-Malone et al. (2012) similarly emphasized the value of realist synthesis for understanding how interventions may operate under different implementation conditions.

Fourth, military facility types were classified into application models. These included barracks and living quarters, medical and isolation spaces, command-and-control rooms, training and education spaces, and naval or enclosed operational spaces. Each model was examined in terms of occupancy density, air circulation, surface-contact intensity, operational continuity, maintenance burden, safety requirements, and security constraints.

Fifth, a preliminary design framework was developed by integrating system components, evidence categories, safety constraints, and facility-specific deployment requirements. The resulting framework consists of five core modules: the catalytic reaction module, airflow and HVAC integration module, filtration and deodorization module, sensing and control module, and monitoring or management module.

Sixth, a staged field-demonstration logic was developed to address the absence of direct military validation data. This stage identified what should be measured before broader deployment, including $H_2O_2$, ozone, VOCs, $CO_2$, PM, temperature, humidity, microbial indicators, device status, operating history, maintenance events, and user feedback.

**Table 1:** Data Collection and Analytical Procedure

| Item | Description |
|---|---|
| Study type | Preliminary design-framework and evidence-mapping study |
| Research purpose | To develop a military-specific preliminary design framework for active air disinfection systems using CHARR as a reference architecture |
| Main object of analysis | Active air disinfection system design requirements for military facilities |
| Role of CHARR | Reference architecture, not a field-validated product |
| Evidence interpretation | Design-relevant evidence, not direct proof of military-field effectiveness |
| Source types | Peer-reviewed literature, technical reports, laboratory and chamber test summaries, hospital or healthcare application materials, safety and conformity documents, product specifications, and military facility requirements |

| | |
|---|---|
| Search databases and source platforms | Google Scholar, PubMed, ScienceDirect, KCI, RISS, official institutional websites, technical reports, and manufacturer-associated technical materials |
| Search period | [Insert actual search dates, e.g., May 1–10, 2026] |
| Main English search terms | "active air disinfection," "military barracks," "indoor air quality," "UVGI," "photocatalytic oxidation," "hydrogen peroxide disinfection," "HVAC disinfection," "airborne infection," "surface bioburden," "room decontamination," "design framework," and "implementation feasibility" |
| Main Korean search terms | "military barracks," "military living quarters," "indoor air quality," "air disinfection," "ventilation," "infection reduction," "photocatalytic oxidation," "hydrogen peroxide disinfection," "HVAC system," "military facility modernization," and "facility safety monitoring" |
| Inclusion criteria | Materials were included if they addressed active air disinfection, indoor air quality, ventilation, filtration, UVGI, photocatalytic or catalytic air treatment, hydrogen peroxide-based disinfection, microbial-burden reduction, safety monitoring, HVAC integration, or military/high-occupancy facility application |
| Exclusion criteria | Materials were excluded if they were purely promotional, lacked identifiable technical content, did not describe system configuration or test conditions, duplicated other sources, or were unrelated to indoor air disinfection, environmental safety, military facilities, or high-occupancy indoor environments |
| Screening approach | Titles, abstracts, executive summaries, technical descriptions, test conditions, reported outcomes, safety information, and deployment relevance were reviewed |
| Evidence classification | Evidence was classified into technical mechanism, air-treatment evidence, surface microbial-burden evidence, safety evidence, HVAC integration evidence, monitoring evidence, and military deployment relevance |
| Analytical procedure | Six-stage analysis: component identification, functional evidence classification, evidence-to-requirement mapping, military facility application modeling, preliminary framework development, and staged field-demonstration logic |
| Output of analysis | Five-module system architecture, facility-specific application models, safety and monitoring criteria, staged deployment pathway, and Go/No-Go criteria |
| Validation logic | Conceptual and design validation through alignment of technical mechanism, prior evidence, safety requirements, and military operational needs |
| Main limitation | No direct military field validation, no infection-incidence measurement, no clinical outcome measurement, and partial reliance on manufacturer-associated or proprietary technical materials |
| Required next step | Pilot field demonstration in representative military facilities under controlled monitoring conditions |

## 3.5. Design Framework Development

The design framework was developed through evidence-to-requirement mapping. Each source category was linked to a corresponding design implication. Laboratory and chamber tests informed the need for controlled airflow, exposure-time assumptions, and microbial-reduction monitoring. Hospital application reports informed the need for continuous operation, surface microbial-burden tracking, and integration with existing cleaning protocols. Safety reports informed the need for $H_2O_2$, ozone, VOC, and by-product monitoring. Product specifications informed module sizing, airflow capacity, installation type, and maintenance requirements.

The framework-development process was informed by prior work on design theory and artifact construction. Walls et al. (1992) argued that information system design theory should provide prescriptive design knowledge linking design requirements and design products. Gregor and Jones (2007) further clarified the structure of design theory by identifying elements such as purpose and scope, constructs, principles of form and function, artifact mutability, testable propositions, and justificatory knowledge. Nickerson et al. (2013) also proposed a systematic method for taxonomy development, emphasizing the iterative classification of

objects according to conceptual and empirical criteria. These studies support the approach used here: recurring system components and design requirements were abstracted into a modular architecture and facility-specific application taxonomy.

The proposed architecture was defined as a multi-module system rather than a stand-alone device. The framework includes the following five modules:

1. Catalytic reaction module: catalytic honeycomb cell, UVx or UV-C light source, and active oxidant generation pathway.

2. Airflow and HVAC integration module: fan, duct interface, air circulation pathway, room-level airflow control, and facility-level HVAC compatibility.

3. Filtration and deodorization module: pre-filter, optional VOC or odor-control filter, particulate pre-treatment, and odor-management function.

4. Sensing and control module: $CO_2$, PM, VOC, temperature, humidity, $H_2O_2$, ozone, device-status sensing, and fault detection.

5. Monitoring and management module: local dashboard, alarm function, maintenance reporting, operating history, user feedback, and optional centralized reporting where permitted.

This modular structure was selected because military deployment requires scalability, maintainability, safety assurance, and staged integration. In the initial stage, a system may operate as a local, ceiling-mounted, or stand-alone unit. In the second stage, it may be connected to room-level environmental sensors. In the third stage, it may be integrated with building-level HVAC or duct systems. In the final stage, it may be connected to local or centralized facility-management systems, subject to security approval.

## 3.6. Military Facility Application Modeling

Military facility application models were developed by matching system functions with the operational characteristics of each facility type. The purpose of this modeling was not to prescribe a final installation plan, but to identify preliminary design priorities for future field demonstration.

The modeling logic was informed by implementation research. Proctor et al. (2011) distinguished implementation outcomes such as acceptability, adoption, appropriateness, feasibility, fidelity, implementation cost, penetration, and sustainability from clinical or service outcomes. This distinction is important for the present study because the framework does not evaluate infection outcomes; instead, it identifies what should be assessed before military deployment. Glasgow et al. (1999) also proposed the RE-AIM framework, emphasizing reach, effectiveness, adoption, implementation, and maintenance as dimensions for evaluating real-world intervention impact. These dimensions informed the staged logic of local testing, operational acceptability, maintenance feasibility, and future scale-up.

The barracks model focuses on high-occupancy living spaces where personnel sleep, rest, store personal items, and repeatedly use shared surfaces. The primary design priorities are continuous occupied-space operation, odor control, mold and humidity-related risk monitoring, low noise, simple maintenance, and user acceptance. The medical and isolation facility model focuses on medical rooms, isolation spaces, and treatment areas. The main design priorities are air and surface microbial-burden management, compatibility with existing cleaning protocols, safety monitoring, documentation of operating history, and periodic environmental sampling.

The command-and-control model focuses on operational rooms where personnel remain for long periods and mission continuity is critical. The design priorities are low-noise operation, continuous air treatment, stable environmental monitoring, minimal operational interruption, fault alarms, and local dashboard-based management. The training and education facility model focuses on classrooms, lecture rooms, and recruit training spaces. The design priorities are variable occupancy response, $CO_2$ and ventilation proxy monitoring, airflow management, odor and VOC control, and periodic reporting.

The naval or enclosed operational-space model focuses on shipboard compartments or other enclosed mission spaces. The design priorities are humidity tolerance, compact installation, corrosion consideration, odor control, limited maintenance access, safe operation in confined environments, and conservative field validation.

## 3.7. Safety and Operational Design Criteria

Safety criteria were derived from the reviewed safety summaries and conformity documents. Because CHARR/NCC-type devices are designed to generate low-level oxidizing species, $H_2O_2$ and ozone must be treated as primary safety-monitoring parameters. Existing safety summaries report no ozone detection and low-level $H_2O_2$ concentrations under tested hospital and public

transportation conditions, while chemical safety assessments illustrate the need to evaluate $H_2O_2$ release under controlled airflow, temperature, and humidity conditions.

For military deployment, the following safety and operational criteria were incorporated into the preliminary design framework:
- $H_2O_2$ concentration monitoring under occupied conditions.
- Ozone monitoring during commissioning and periodic operation.
- VOC and by-product assessment where required.
- $CO_2$, PM, temperature, and humidity monitoring for environmental quality.
- Noise-level evaluation, especially in sleeping quarters and command rooms.
- Electrical safety and compatibility with existing facility systems.
- Maintenance procedure standardization.
- Filter and catalytic-module replacement planning.
- Local operation capability when network connection is restricted.
- Manual override and fault alarm functions.
- Documentation of operating time, alarm history, maintenance events, and user feedback.

These criteria are intended to ensure that active air disinfection systems are not introduced as isolated treatment devices but as managed environmental-control systems with traceable safety and operating records. This approach is consistent with Moore et al. (2015), who emphasized that process evaluation of complex interventions should examine implementation, mechanisms, and context. In military facilities, the same logic applies: technology performance cannot be interpreted without considering installation context, user behavior, maintenance, safety monitoring, and organizational constraints.

## 3.8. Preliminary Validation Logic and Study Limitations

This study uses a preliminary design-validation logic rather than an experimental-validation logic. The framework is conceptually validated by aligning four elements: technical mechanism, prior test evidence, safety documentation, and military operational requirements. This approach is appropriate for an early-stage system design paper because the purpose is to define what should be built, installed, monitored, and tested in a future military field demonstration.

The field-demonstration logic was informed by feasibility-study methodology. Bowen et al. (2009) argued that feasibility studies can examine acceptability, demand, implementation, practicality, adaptation, integration, expansion, and limited-efficacy testing before full-scale research. In the present study, this logic supports staged evaluation before military-wide deployment. Thus, the proposed Go/No-Go criteria should be understood as preliminary feasibility and implementation criteria, not as final clinical or epidemiological validation criteria.

However, the study has several limitations. First, most of the reviewed technical and testing materials were not generated in military environments. Second, laboratory and hospital findings cannot be directly generalized to barracks, ships, command rooms, or training centers. Third, some materials are manufacturer-associated reports or proprietary summaries, and therefore their findings should be interpreted cautiously. Fourth, this study does not measure infection incidence, clinical outcomes, or direct operational readiness effects. Fifth, the proposed framework has not yet been validated through actual military field data.

Despite these limitations, the framework provides a necessary intermediate step between technical possibility and military deployment. It identifies system components, facility-specific application models, safety criteria, operational variables, and future field-demonstration requirements. Thus, the proposed preliminary design framework can serve as a foundation for pilot studies, procurement evaluation, military facility modernization planning, and indoor air management policy development.

**Table 2:** Methodological Positioning of This Study

| Aspect | Description |
|---|---|
| Study type | Preliminary design-framework study |
| Validation type | Conceptual and design validation, not experimental validation |
| Role of CHARR | Reference architecture for active air disinfection system design |
| Evidence use | Design-relevant evidence, not direct proof of military effectiveness |
| Main outputs | System architecture, facility-specific application models, safety criteria, field-demonstration requirements |
| Main limitation | No direct military field validation data |
| Required next step | Pilot field demonstration in representative military facilities |

As shown in Table 2, the study used a structured evidence-mapping procedure rather than an experimental

performance-validation design. The collected materials were not treated as direct evidence that CHARR/NCC-type systems are effective in military facilities. Instead, they were used to identify design variables, safety requirements, monitoring parameters, facility-specific application conditions, and staged validation needs. This approach is appropriate because the objective of the study is to define a preliminary design framework for future field demonstration, not to verify clinical, epidemiological, or operational outcomes.

## 4. Research Results and Discussion

### 4.1. Overview of the Design Evidence

The reviewed materials indicate that active air disinfection systems should be conceptualized as multifunctional environmental-control systems rather than as stand-alone air-cleaning devices. Across the reviewed technical reports, controlled test materials, hospital application documents, and peer-reviewed studies, five recurring design functions were identified: catalytic or active treatment, airflow integration, air and surface microbial-burden management, safety monitoring, and operational management.

The evidence base does not directly validate the effectiveness of CHARR or any other active air disinfection system in military facilities. However, it provides design-relevant information for developing a preliminary military application framework. Prior studies on healthcare environmental contamination show that contaminated surfaces can contribute to pathogen transmission and that improved environmental cleaning and disinfection may reduce healthcare-associated infection risks (Weinstein & Hota, 2004; Kramer et al., 2006; Dancer, 2008, 2009; Otter et al., 2011, 2013a; Donskey, 2013). Studies on automated ultraviolet and hydrogen peroxide-based room decontamination also show that active environmental technologies can reduce microbial contamination under defined conditions (Andersen et al., 2006; Boyce et al., 2008; Nerandzic et al., 2010; Fu et al., 2012; Anderson et al., 2013, 2017; Rutala et al., 2010).

Therefore, the main result of this synthesis is that active air disinfection systems for military facilities should be designed as integrated architectures consisting of treatment, circulation, monitoring, safety verification, and operational-management functions. This system-level interpretation is particularly relevant to military facilities because such facilities require continuous operation, simple maintenance, occupied-space safety, and standardized deployment across different facility types.

The main result of this synthesis is that active air disinfection systems for military facilities should be designed as integrated architectures consisting of treatment, circulation, sensing, safety, and management functions. This architecture is particularly relevant to military facilities because such facilities require continuous operation, simple maintenance, occupied-space safety, and standardized deployment across different facility types.

### 4.2. Preliminary System Architecture

The first major result is the development of a five-module preliminary system architecture. The reviewed evidence suggests that active air disinfection should not be understood only as a treatment device. For practical deployment in military facilities, it must be integrated with airflow, filtration, sensing, safety control, and operational management functions.

The proposed preliminary architecture consists of the following five modules.

1. Catalytic reaction module
This module includes the catalytic honeycomb cell, UVx or UV-C light source, and active oxidant generation pathway. In the CHARR-based reference architecture, this module is responsible for generating low-level oxidizing species from ambient air and moisture. However, the literature on room decontamination and environmental disinfection indicates that active treatment modules should be interpreted cautiously and evaluated under defined operating conditions rather than assumed to be universally effective (Rutala et al., 2010; Nerandzic et al., 2010; Anderson et al., 2013).

2. Airflow and HVAC integration module
This module includes fans, ducts, air circulation pathways, room-level airflow control, and facility-level HVAC compatibility. Studies on UV-C room decontamination and automated terminal disinfection demonstrate that microbial reduction depends on exposure conditions, room configuration, line-of-sight limitations, treatment time, and environmental context (Rutala et al., 2010; Anderson et al., 2013, 2017). Therefore, military deployment should define airflow pattern, room volume, placement, and duct or ceiling integration before field use.

3. Filtration and deodorization module
This module includes pre-filters, particulate control, VOC reduction, and odor-control elements. In military spaces, this module is important because indoor air problems include not only microorganisms but also odors, VOCs, dust, mold-related conditions, and humidity-related

contamination. It also serves as a pre-treatment layer that can reduce particle load before active treatment.

4. Sensing and control module
This module includes $CO_2$, PM, VOC, temperature, humidity, $H_2O_2$, ozone, device status, filter condition, and operating-time sensors. The need for sensing and control is supported by studies showing that environmental disinfection outcomes depend on actual operating conditions, exposure time, and process repeatability (Fu et al., 2012; Otter et al., 2013b; Boyce, 2016). Therefore, monitoring should be treated as part of the system architecture rather than as an optional add-on.

5. Monitoring and management module
This module includes local dashboards, alarm functions, maintenance logs, operating history, and optional centralized reporting. In military settings, this module must be designed with security and network-separation constraints in mind. Studies on no-touch automated room disinfection emphasize that process repeatability, operational practicality, and documentation are important when environmental technologies are introduced into occupied facilities (Otter et al., 2013b; Boyce, 2016). The preliminary architecture is presented in Figure 1.

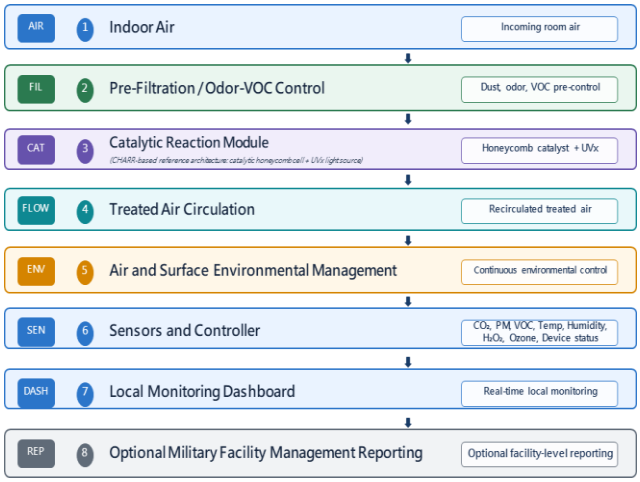


**Figure 1:** Preliminary Active Air Disinfection System Architecture for Military Facilities

This architecture shows that active air disinfection deployment in military facilities should not be framed as the installation of a single air purifier. Rather, it should be framed as a modular environmental management system that combines air treatment, surface-risk reduction, monitoring, safety control, and maintenance reporting.

## 4.3. Evidence-to-Requirement Mapping

The second major result is the development of an evidence-to-requirement mapping structure. The reviewed documents and peer-reviewed studies provide different types of evidence, but not all evidence has the same design meaning. Laboratory and room-decontamination studies support technical feasibility under defined conditions. Healthcare environmental studies support the concept of surface-risk management.

Safety and process-comparison studies support the need for monitoring and commissioning. Therefore, this study translated each evidence category into military design requirements rather than treating prior evidence as direct proof of military effectiveness.

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**Table 3:** Evidence-to-Requirement Mapping

| Evidence category | Representative peer-reviewed support | Design interpretation | Military design requirement |
|---|---|---|---|
| Environmental surface contamination | Weinstein & Hota (2004); Kramer et al. (2006); Otter et al. (2011) | Contaminated surfaces can act as reservoirs for pathogens. | Include surface-risk zones in design and evaluation. |

| | | | |
|---|---|---|---|
| Environmental cleaning and infection control | Dancer (2008, 2009); Donskey (2013) | Cleaning and disinfection are relevant to infection-control outcomes. | Treat active disinfection as a supplement to cleaning, not a replacement. |
| No-touch room disinfection | Otter et al. (2013b); Boyce (2016) | Automated technologies improve process consistency but require context-specific implementation. | Include operating logs, alarms, maintenance records, and user training. |
| UV-C room decontamination | Rutala et al. (2010); Nerandzic et al. (2010); Anderson et al. (2013) | UV-C devices can reduce selected pathogens under defined room conditions. | Define exposure time, placement, room geometry, and line-of-sight limitations. |
| Hydrogen peroxide-based decontamination | Andersen et al. (2006); Boyce et al. (2008); Cooper et al. (2011); Fu et al. (2012) | $H_2O_2$ systems can reduce environmental contamination but require safety and process control. | Require $H_2O_2$ monitoring, commissioning, and room re-entry criteria. |
| Enhanced terminal disinfection | Anderson et al. (2017) | Enhanced disinfection strategies can reduce acquisition or infection in healthcare settings. | Use staged field validation before scaling to military facilities. |
| Hospital surface transmission | Weber et al. (2010); Otter et al. (2013a) | Surface-mediated transmission is a recognized component of environmental infection risk. | Combine air treatment with high-touch surface management. |

This mapping is important because it prevents overinterpretation of prior evidence. The results do not indicate that active air disinfection systems have already been proven effective in military barracks. Instead, they indicate that CHARR/NCC-type systems can be used as a reference architecture for a structured field-demonstration framework, provided that deployment is guided by monitoring, safety verification, and facility-specific validation.

The third result is the identification of military-specific design requirements. Military facilities differ from hospitals and civilian buildings because they involve collective living, command readiness, restricted maintenance windows, security constraints, and standardized operation across large numbers of facilities.

The analysis identified eight core military design requirements.

## 4.4. Military Facility Design Requirements

**Table 4:** Military Design Requirements for Active Air Disinfection Deployment

| Requirement | Description | Design response |
|---|---|---|
| Continuous occupancy | Barracks, command rooms, and medical spaces may be occupied for long periods. | Use low-concentration occupied-space operation with safety monitoring. |
| High occupancy density | Living quarters and training spaces may have many personnel in one room. | Size systems by room volume, occupancy density, and airflow pattern. |
| Air and surface exposure | Shared surfaces and shared air coexist in military spaces. | Combine air treatment with surface-risk management. |
| Low operational burden | Military facility managers require simple, repeatable maintenance. | Use modular cartridges, scheduled replacement, and alarm-based maintenance. |
| Safety assurance | Personnel may sleep or work near operating units. | Monitor $H_2O_2$, ozone, VOCs, temperature, humidity, and noise. |
| Security constraints | Central network connection may be limited. | Use local dashboard first; central reporting only after |

| | | |
|---|---|---|
| | | approval. |
| Scalability | Deployment may expand from one room to multiple buildings or units. | Use standardized ceiling, duct, and HVAC-linked configurations. |
| Mission continuity | Equipment failure should not disrupt operations. | Include fault alarms, manual override, and maintenance logs. |

These requirements show that military deployment requires a more conservative design logic than ordinary commercial installation. In particular, safety, maintainability, and security must be treated as core design elements rather than afterthoughts.

## 4.5. Facility-Specific Application Models

The fourth result is the development of five facility-specific application models: barracks, medical facilities, command-and-control spaces, training facilities, and naval or enclosed operational spaces. Each model requires different design priorities.

### 4.5.1. Barracks and Living Quarters Model

The barracks model is designed for military living spaces where personnel sleep, rest, store personal items, and repeatedly use shared surfaces. The main risks include high occupancy density, odor, humidity, mold, respiratory transmission, and surface recontamination. Because studies have shown that environmental surfaces can remain contaminated for extended periods and may contribute to transmission risk, barracks design should include both air treatment and high-touch surface management (Kramer et al., 2006; Otter et al., 2011, 2013a).

The recommended design priorities are:

- low-noise continuous operation;
- room-volume-based unit sizing;
- odor and VOC control;
- humidity and mold-risk monitoring;
- $H_2O_2$and ozone safety verification;
- simple filter and module maintenance;
- local operating-status display.

### 4.5.2. Medical and Isolation Facility Model

The medical facility model is designed for military medical rooms, isolation spaces, and treatment areas. The main risks include patient movement, high-touch surfaces, respiratory symptoms, and environmental contamination. Because hospital studies show that enhanced disinfection technologies can reduce environmental bioburden under defined conditions, military medical spaces should apply higher monitoring and documentation standards than ordinary barracks (Boyce et al., 2008; Nerandzic et al., 2010; Anderson et al., 2013, 2017).

The recommended design priorities are:

- air and surface microbial-burden management;
- compatibility with existing cleaning protocols;
- higher documentation level;
- operating-history recording;
- safety monitoring under occupied conditions;
- periodic microbial and air-quality sampling.

In this model, active air disinfection should not replace cleaning or medical infection-control procedures. It should be designed as a supplementary environmental control layer.

### 4.5.3. Command-and-Control Facility Model

The command-and-control model applies to situation rooms, operations centers, air-defense rooms, communication rooms, and other mission-critical spaces. These facilities often require long-duration occupancy, low noise, high reliability, and minimal operational interruption. Because no-touch disinfection and room-decontamination studies emphasize process repeatability and operational feasibility, command facilities require reliable local monitoring, fault detection, and maintenance scheduling (Otter et al., 2013b; Boyce, 2016).

The recommended design priorities are:

- low-noise operation;
- uninterrupted continuous air treatment;
- local dashboard monitoring;
- minimal user intervention;
- maintenance scheduling outside operational hours;
- redundancy or backup operation where needed;
- no unauthorized network connection.

### 4.5.4. Training and Education Facility Model

The training facility model applies to classrooms, lecture rooms, recruit training spaces, and indoor instruction areas. These spaces may have variable occupancy depending on training schedules. The design priorities are variable occupancy response, $CO_2$ and ventilation proxy monitoring, airflow management, odor and VOC control, and periodic

reporting.

For training spaces, integration with occupancy scheduling and ventilation management may be more important than continuous 24-hour operation.

#### 4.5.5. Naval and Enclosed Operational Space Model

The naval or enclosed operational-space model applies to shipboard living quarters, CIC rooms, enclosed compartments, and other limited-volume military environments. These spaces may face humidity, odor, corrosion, restricted maintenance access, and limited installation space. Because hydrogen peroxide-based and UV-based decontamination systems require careful control of exposure conditions, re-entry criteria, and safety verification, enclosed military spaces require the most conservative field validation (Andersen et al., 2006; Fu et al., 2012; Rutala et al., 2010).

The recommended design priorities are:

- compact installation;
- humidity and corrosion consideration;
- odor and VOC control;
- low-maintenance operation;
- careful airflow distribution;
- safety monitoring in confined spaces;
- compatibility with shipboard power and ventilation systems.

### 4.6. Staged Deployment and Go/No-Go Criteria

The fifth result is a staged deployment model with preliminary Go/No-Go criteria. Because military facilities have security, maintenance, and approval constraints, full-scale centralized deployment should not be the initial step. Instead, deployment should proceed in stages, and each stage should be evaluated before moving to the next level. in stages, and each stage should be evaluated before moving to the next level.

**Table 5:** Staged Deployment Model and Preliminary Go/No-Go Criteria

| Stage | Deployment level | Main purpose | Required output | Preliminary Go/No-Go criteria |
|---|---|---|---|---|
| Stage 1 | Stand-alone or ceiling-mounted unit | Verify local operation, safety, and user acceptance | Installation report, safety measurement, operating log | No ozone detection; $H_2O_2$ remains within predefined safety threshold; no major user complaint |
| Stage 2 | Room or zone-level sensor integration | Link air treatment with environmental monitoring | $CO_2$, VOC, PM, humidity, $H_2O_2$, ozone data | Stable sensor operation; valid data logging; no abnormal chemical reading |
| Stage 3 | HVAC or duct integration | Expand treatment to facility-level airflow | Airflow evaluation, duct compatibility report | No major airflow imbalance; acceptable noise level; maintenance access confirmed |
| Stage 4 | Local dashboard management | Support facility manager decision-making | Alarm, operating status, maintenance report | Alarm response verified; maintenance log completed; operator usability confirmed |
| Stage 5 | Approved central reporting | Enable unit-level or command-level environmental reporting | Standardized dashboard and periodic report | Cybersecurity approval; command approval; standardized reporting protocol established |

The staged model reduces implementation risk. It reflects the logic of prior environmental-disinfection studies, which show that technologies can perform differently depending on room configuration, exposure conditions, process control, and implementation context (Fu et al., 2012; Otter et al., 2013b; Anderson et al., 2017). The preliminary Go/No-Go criteria clarify that military deployment should be evidence-driven rather than assumption-driven.

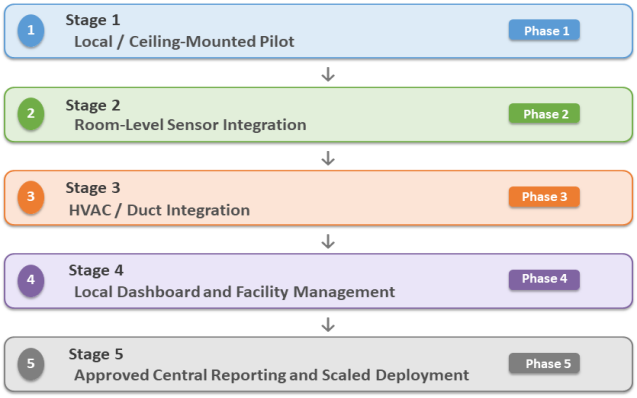


**Figure 2:** Staged Deployment and Validation Pathway for Military Active Air Disinfection Systems

## 4.7. Safety and Monitoring Framework

The sixth result is a safety and monitoring framework. The reviewed evidence indicates that chemical safety, environmental quality, device operation, and operational records should be monitored together. Hydrogen peroxide-based room-decontamination studies show that $H_2O_2$ systems can be effective but require careful process control, safety management, and evaluation of room conditions (Andersen et al., 2006; Boyce et al., 2008; Cooper et al., 2011; Fu et al., 2012). UV-C studies also show that microbial reduction depends on exposure time, line-of-sight, distance, and device placement (Rutala et al., 2010; Nerandzic et al., 2010; Anderson et al., 2013).

**Table 6:** Safety and Monitoring Framework

| Monitoring layer | Parameters | Purpose |
|---|---|---|
| Chemical safety | $H_2O_2$, ozone, VOCs, by-products | Confirm occupied-space safety |
| Environmental quality | $CO_2$, PM, temperature, humidity | Monitor ventilation, dust, comfort, and mold-risk conditions |
| Device operation | fan status, lamp status, module life, filter status | Ensure system reliability |
| Operational record | operating time, alarms, maintenance events, manual override | Support military facility management and reporting |

This safety framework is essential because military deployment requires not only effectiveness but also traceability, accountability, and repeatable operation.

## 4.8. Final Preliminary Design Framework

The final result of the study is an integrated preliminary design framework that combines system architecture, evidence-to-requirement mapping, facility-specific application models, staged deployment, and safety monitoring. The proposed framework consists of four layers.

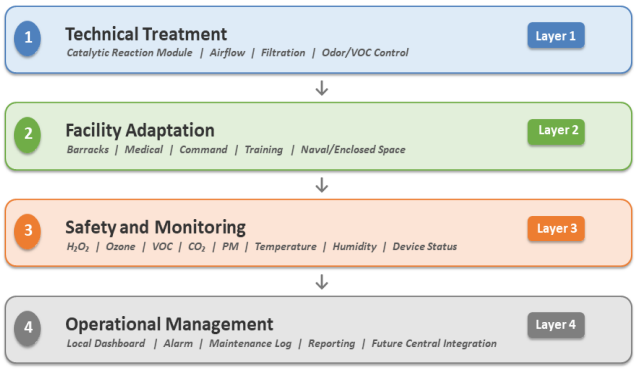


**Figure 3:** Final Preliminary Design Framework for Military Active Air Disinfection Systems

The framework shows that active air disinfection systems should be introduced into military facilities as managed environmental-control platforms. The design must address not only microbial reduction but also safety, facility compatibility, operational continuity, maintainability, and documentation.

## 4.9. Summary of Research Results

The research results can be summarized as follows.
First, active air disinfection systems for military facilities should be designed as multi-module systems consisting of catalytic reaction, airflow integration, filtration and deodorization, sensing and control, and monitoring functions.
Second, prior laboratory, chamber, and hospital materials provide design-relevant evidence, but they should not be interpreted as direct proof of military-field effectiveness.

Third, military deployment requires specific design requirements, including occupied-space safety, high-density operation, air-plus-surface management, low maintenance burden, security-aware monitoring, and scalability.
Fourth, five application models are proposed: barracks, medical facilities, command-and-control rooms, training facilities, and naval or enclosed operational spaces.

Fifth, staged deployment is necessary. The system should begin with local or ceiling-mounted operation, then move to sensor integration, HVAC linkage, local dashboard management, and, only where approved, central reporting.

Sixth, preliminary Go/No-Go criteria should be applied at each deployment stage to avoid premature scale-up.

Seventh, H2O2, ozone, VOCs, $CO_2$, PM, temperature, humidity, and device status should be incorporated into a safety and monitoring framework.

Overall, the results indicate that CHARR/NCC-type systems can be meaningfully used as a reference architecture for military active air disinfection system design, provided that deployment is guided by facility-specific design, safety monitoring, operational management, staged validation, and future field demonstration.

## 5. Conclusions

This study developed a preliminary design framework for active air disinfection systems in military facilities, using CHARR as a reference architecture. The purpose of the study was not to conduct a new laboratory experiment, field trial, or direct performance validation in military environments. Rather, the study synthesized available technical reports, laboratory and chamber test summaries, hospital application materials, safety documents, product specifications, and military facility requirements to propose a structured system architecture for future military field demonstration.

The findings suggest that active air disinfection systems should not be understood as stand-alone air-cleaning devices. Instead, they should be designed as modular environmental management systems that integrate catalytic air treatment, airflow control, filtration and deodorization, sensing and safety monitoring, and operational management. This system-level interpretation is especially important in military facilities, where indoor air management is closely related to collective living, infection-risk reduction, facility modernization, operational continuity, and troop health protection.

The proposed preliminary framework consists of five core modules: the catalytic reaction module, the airflow and HVAC integration module, the filtration and deodorization module, the sensing and control module, and the monitoring and management module. In the CHARR-based reference architecture, the catalytic reaction module includes a catalytic honeycomb cell, UVx or UV-C light source, and active oxidant generation pathway. However, the framework itself is not limited to one device configuration; it is intended to guide the design, monitoring, and field evaluation of active air disinfection systems for military facilities.

The framework can be configured differently depending on the characteristics of the target facility. Barracks require low-noise, continuous, occupied-space operation and odor, humidity, and mold-risk management. Medical and isolation facilities require stronger air-and-surface microbial-burden monitoring and documentation. Command-and-control rooms require stable operation, low noise, local monitoring, and minimal operational interruption. Training facilities require occupancy-responsive operation and $CO_2$-based ventilation proxy monitoring. Naval and enclosed operational spaces require compact installation, humidity tolerance, corrosion consideration, and strict safety verification.

A major conclusion of this study is that prior laboratory, chamber, and hospital evidence should be used as design-relevant evidence, not as direct proof of military-field effectiveness. Existing reports suggest that CHARR/NCC-type systems may reduce selected airborne and surface microbial burdens under controlled or healthcare-related conditions. However, military environments differ substantially from laboratories and hospitals in terms of occupancy density, spatial layout, airflow conditions, maintenance systems, mission requirements, and security restrictions. Therefore, the appropriate next step is not immediate large-scale deployment, but structured field demonstration in selected military facilities.

The study also emphasizes that safety and monitoring must be built into the design from the beginning. Because catalytic active air disinfection systems may generate low-level oxidizing species, parameters such as $H_2O_2$, ozone, VOCs, temperature, humidity, particulate matter, and device operating status should be incorporated into commissioning, operation, and reporting procedures. In military settings, where personnel may sleep, train, work, or conduct missions in the same spaces where the system operates, occupied-space safety and traceable operating records are essential.

From an implementation perspective, the study recommends a staged deployment model with preliminary Go/No-Go criteria. The first stage should focus on stand-alone or ceiling-mounted local operation in selected facilities. The second stage should add environmental sensors and room-level monitoring. The third stage should evaluate HVAC or duct integration where facility infrastructure allows. The fourth stage should introduce local dashboard-based management for facility personnel. Centralized reporting should be considered only after security, network, and command-level approval. At each stage, progression should depend on safety measurements, sensor stability, airflow compatibility, user acceptance, maintenance feasibility, and command approval.

This study has several limitations. First, it relies on existing technical, laboratory, hospital, and safety documents rather than newly generated military field data. Second, some reviewed materials are manufacturer-associated technical reports or proprietary summaries, which require cautious interpretation. Third, the proposed framework has not yet been tested in actual barracks, command facilities, medical rooms, training centers, or naval compartments. Fourth, the study does not evaluate clinical infection outcomes, epidemiological effects, or direct readiness improvement. These limitations mean that the framework should be regarded as a preliminary design foundation rather than a completed validation result.

Despite these limitations, the study provides a useful intermediate step between technical possibility and military deployment. It translates existing evidence into military-specific system requirements, identifies facility-specific application models, and proposes safety and monitoring criteria for future field demonstration. The framework can support future pilot studies, procurement evaluation, military facility modernization planning, and indoor air management policy development.

In conclusion, active air disinfection systems, including CHARR/NCC-type catalytic systems, may have strategic relevance for military indoor air management when they are designed and evaluated as integrated environmental-control platforms. Their value lies not only in potential microbial-burden reduction, but also in their ability to support continuous air and surface management, odor and VOC control, environmental monitoring, maintenance reporting, and facility-level operational management. Future research should conduct controlled field demonstrations in representative military facilities, compare treated and untreated spaces, measure air quality and microbial indicators over time, and evaluate safety, maintainability, user acceptance, and operational suitability.

Through such validation, CHARR-based reference architectures can be assessed more rigorously as part of a broader military strategy for healthier, safer, and more resilient indoor environments. In the Korean military context, the proposed framework may also support barracks modernization and institutional indoor air quality management by providing a structured basis for pilot testing, safety monitoring, maintenance documentation, and evidence-based procurement evaluation.

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