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Review Article

Environmental control system (ECS) design approach for collective nuclear, biological, and chemical (NBC) protection in military aircraft: A review

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Abstract

This comprehensive review paper delves into Environmental Control System (ECS) design strategies tailored for collective Nuclear, Biological, and Chemical (NBC) protection in military aircraft, exploring key elements such as hardening, air-tight construction, and filtering within the framework of open-loop or closed-loop ECS configurations. Initially, the paper elucidates the NBC protection requirements stipulated in commonly applied regulations such as MIL-HDBK-516C, DEFSTAN, and EMACC, highlighting the imperative for ventilation air to be devoid of contaminants, as mandated by these regulations. Subsequently, the paper delineates the strategic framework for NBC defense in the military aerospace industry, emphasizing the principles of avoidance, protection, and decontamination. A comparative analysis between individual and collective protection strategies underscores the comprehensiveness of the latter, prompting a recommendation for ECS design approaches grounded in the principles of collective protection, namely hardening, air-tight construction, and filtering. Furthermore, the paper provides insights into the configurations of open-loop and partial closed-loop ECS, elucidating their architectures for NBC protection. A comparative evaluation of these configurations enables the identification of pertinent parameters crucial for informed selection. In conclusion, the paper posits that the partial closed-loop ECS configuration exhibits greater promise in delivering enhanced NBC protection compared to the open-loop configuration, particularly in military aircraft applications operating in NBC environments.

1. Introduction

The Environmental Control System (ECS) stands as a cornerstone in the operational effectiveness of military aircraft, ensuring optimal conditions for both crew and equipment. Responsible for regulating temperature, pressure, humidity, ventilation, and air quality within the cockpit, the ECS plays a vital role in sustaining mission readiness. However, conventional ECS designs may fall short in safeguarding against the hazardous effects of nuclear, biological, or chemical (NBC) attacks.

In light of these challenges, a unique design approach becomes imperative to retrofit ECS systems for collective NBC protection within military aircraft. This paper presents a departure from conventional literature by offering a comprehensive review that explicitly addresses the specialized requirements of ECS systems for NBC protection, a topic that has garnered relatively limited attention in existing studies. The paper covers the following topics: (1) the overview of the NBC threat and the NBC protection's concept, (2) the requirements and specifications of the ECS for the NBC protection, (3) the current

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Through a systematic review, this paper not only synthesizes existing knowledge but also breaks new ground by providing original insights into the intricacies of ECS design as it pertains to NBC protection in military aviation. By identifying gaps and limitations in the current state-of-the-art, it lays the groundwork for potential solutions and recommendations aimed at optimizing ECS performance and fostering innovation. Drawing from advancements in fluid mechanics, thermodynamics, heat transfer and filtration, this paper endeavors to contribute to the collective knowledge base, thereby inspiring further research and development in this critical and complex domain.

2. ECS Design Approaches for Collective NBC Protection in Aircraft

The term NBC refers to the condition in which the threat is posed by nuclear (N), biological (B), and chemical (C) substances or agents [1]. It replaced the term of ABC (atomic, biological, and chemical) that emerged in 1950s since the nuclear warfare is more complex, requiring more specific terms than atomic [2-4]. Chemical, Biological, Radiological, and Nuclear (CBRN) have also emerged to cover the wide range of potential hazards. The article will focus on the term of NBC.

An NBC incident is expressed as an unintentional (accidental) or deliberate (enemy aggression) release of nuclear, biological, or chemical agents [5]. Contamination resulting from the NBC incident, can be transmitted through radiation, vapor, and desorption [6]. Radiation is a form of electromagnetic energy with different wavelengths, as shown in Figure 1[7].

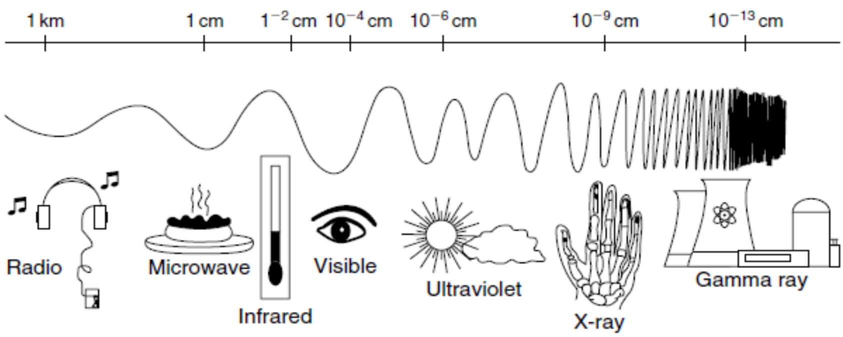

Fig. 1. Electromagnetic Spectrum [8]

Nuclear radiation is unique due to its ionizing capability to remove an electron from the orbit of a target atom or molecule, as shown in Figure 2. Ionization occurs when high energy alpha or beta particles or gamma rays transfer enough energy to remove the electron from orbit.

In nuclear incidents, the particles of alpha, beta, and gamma rays are released into the environment [9]. The ionizing capabilities of these products vary, and they are defined with the specific ionization value, which is the average number of ion pairs per unit length along the path as shown in Table 1.

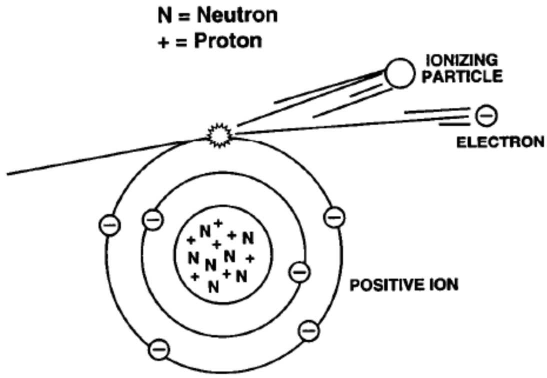

Fig. 2. Removal of an Electron due to Ionizing Particle [8]

The penetration capabilities of nuclear radiation, as depicted in Figure 3, play a crucial role in assessing their impact on human health beyond their ionizing potential. Alpha particles, due to their size, cannot penetrate human skin, thus presenting no immediate external hazard; however, inhalation poses a significant threat. In contrast, beta particles, being smaller, can penetrate multiple layers of skin, resulting in skin burns known as beta burns. Gamma rays, with their ability to traverse several inches through human tissue, pose a considerable risk to human health, often leading to fatal consequences.

Table 1.Specific Ionization of Radiation [10]

Radiation	Range in air	Speeds	Specific ionization
Alpha	5-7 cm	3,200-32,000 km/sec	20,000-50,000 ion pairs/cm
Beta	200-800 cm	25-99% speed of light	50-500 ion pairs/cm
Gamma	Use of half-thickness	Speed of light 300,000 km/sec	5-8 ion pairs/cm

The biological impact of ionization on the human body is profound. When water molecules within human tissue become ionized, they generate free radicals of hydrogen and hydroxyl, which can induce cellular damage, alter cell structures, and spur the production of abnormal cells. Beyond the perilous effects of nuclear substances on human health, they harbor the potential to wreak havoc on aviation electronics, jeopardizing their functionality and even causing operational standstills through mechanisms like ionization, displacement damage, and chemical reactions. Nuclear radiation has the capability to ionize atoms and molecules within electronic devices. A single charged particle can liberate numerous electrons from an atom or molecule, introducing unwanted electrical disturbances known as electronic noise [12], which can disrupt accurate signaling in digital circuits [13-16]. Moreover, nuclear radiation can harm the crystal lattice of semiconductor materials within electronic devices, resulting in defects that ensnare charge carriers and impede electron mobility. Additionally, nuclear radiation can instigate chemical reactions that culminate in the formation of corrosive byproducts within electronic devices [17-21].

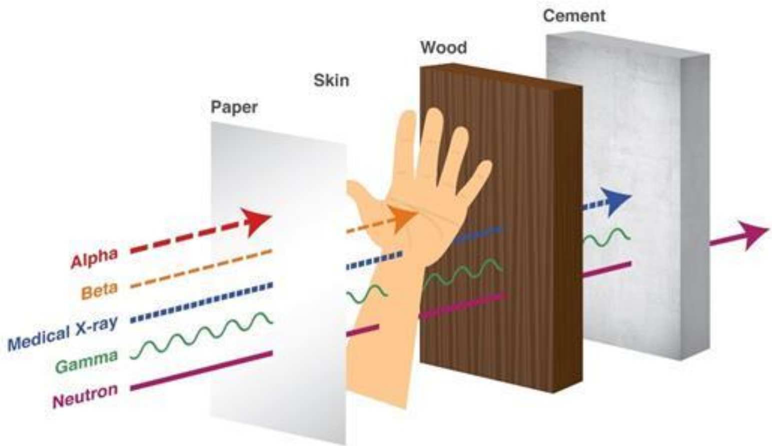

Fig. 3. Penetrating Capabilities of Nuclear Substances [11]

During biological incidents, hazardous agents including bacteria, viruses, and toxins, as outlined in Table 2, can be discharged into the environment [22-23], triggering substantial adverse effects on human health.

Table 2. Potential Biological Agents [24]

Group	Disease	Likely Methods of Dissemination	Incubation Time	Duration of Illness	Lethality
Bacteria	Anthrax	Spores in aerosols	1-6 days	3-5 days	High
	Brucellosis	1. Aerosol 2. Sabotage	Days to months	Weeks to years	Low
	Cholera	1. Aerosol 2. Sabotage	1-5 days	1 or more weeks	Moderate to high
	Melioidosis	Aerosol	Days to years	4-20 days	Variable
	Plague	1. Aerosol 2. Infected vectors	2-3 days	1-2 days	Very high
	Tularemia	Aerosol	2- 10 days	2 or more weeks	Moderate if untreated
	Typhoid Fever	1. Aerosol 2. Sabotage	7-21 days	Several weeks	Moderate if untreated
Rickettsiae	Epidemic Typhus	1. Aerosol 2. Infected vectors	6-16 days	Weeks to months	High
	Q-Fever	1. Aerosol 2. Sabotage	10-20 days	2 days to 2 weeks	Very low
	Scrub Typhus	1. Aerosol 2. Infected vectors	4-15 days	Up to 16 days	Low
Chlamydia	Psittacosis	Aerosol	4-15 days	Weeks to months	Very low
	Coccidioidomycosis	Aerosol	1-2 weeks	Weeks to months	Low

	Histoplasmosis	Aerosol	1-2 weeks	Weeks to months	Low
Viruses	Chikun-Gunya Fever	Aerosol	2-6 days	2 weeks	Very low
	Crimean-Congo Hemorrhagic Fever	Aerosol	3-12 days	Days to weeks	High
	Dengue Fever	Aerosol	3-6 days	Days to weeks	Low
	Eastern Equine Encephalitis	Aerosol	5-15 days	1-3 weeks	High

Additionally, these biological agents pose a notable threat to avionics systems. They have the potential to develop biofilms on surfaces, disrupting signaling processes and impeding performance. Moreover, these biofilms can act as barriers, diminishing the cooling efficiency of avionics. Furthermore, they may infiltrate organic components within avionics, such as sealants and lubricants, leading to leaks and other operational malfunctions [25-29].In chemical incidents, hazardous chemical substances such as the nerve, blister, choking, or blood agents, may be released [30].

The lethality of NBC agents presents how fatal they are, considering that it varies with agent type, exposure type, dosage, and individual susceptibility, as shown in Table 3.

Table 3. Lethality of NBC Agents [31-39]

Group	Agent	Lethality Rate
Nuclear Agents	Including alpha, beta particles, and gamma ray	Fatal
Biological Agents	Anthrax (spores, inhaled)	10-80%
	Ebola (direct contact with bodily fluids)	50-90%
	Plague (pneumonic form)	90-100%
	Smallpox (inhaled)	30-60%
	Botulinum Toxin	60-90%
Chemical Agents	Methylphosphonothioic acid (nerve agent, inhaled)	90-100%
	Sarin (nerve agent, inhaled)	70-90%
	Mustard gas (blister agent, inhaled)	50-70%
	Chlorine gas (choking agent, inhaled)	10-30%
	Cyanide (blood agent, inhaled)	90-100%

NBC effects on human health are variable with respect to type of agent, its dosage, and route of exposure [40]. Different types of NBC agents lead to distinct effects, such as irradiation from radiation exposure, infection from exposure to live biological agents, and intoxication from chemical exposure [41-42]. The toxic effects of the agents upon humans range from sickness to death, temporary or long-term and often manifest within seconds or minutes of exposure. However, avionics may not exhibit signs of any degradation for long periods, such as weeks or months. NBC impact on avionics may be more significant since decontamination process would give additional damage when the equipment is washed in a corrosive solution [24].

In the current era, the clandestine pursuit of scientific studies and the escalation of regional arms races without adequate arms control measures are a great concern since their consequences may result in catastrophic conditions [43]. In the civil world, the case of the coronavirus is the most recent example of a situation that caused the whole world to lock down. Moreover, the widening gap in military power between nations may prompt less advantaged states to seek a balance of power through the development of NBC weaponry. The deployment of tactical nuclear weapons in the Russia-Ukraine war and North Korea's nuclear missile tests are some of the examples that sustain this concern today. In such circumstances, aircraft crew and avionics may be exposed to NBC agents since military air vehicles are at the forefront of military operations or war.

NBC's threat is more likely than ever, whether it is due to an accident or an enemy's aggression. For this reason, NBC defense measures play a pivotal role in the design and certification process of military aircraft, ensuring compliance with NBC protection standards. These standards are delineated in various widely recognized regulations, including MIL-HDBK-516C from the U.S., DEF-STAN from the U.K., and EMACC from the European Union.

MIL-HDBK-516C states that [44] "Verify that the operators'/crew members' breathing air is protected from contamination in all forms, including oil leakage in the engine and nuclear, biological, and chemical (NBC) warfare conditions". Similarly, EMACC gives an explanation that [45] "NBC protection equipment and procedures shall be provided so that ventilation air is free from the contaminants".

Furthermore, DEF-STAN claims that [46] "The Aircraft and its installed equipment shall be designed to be operated by personnel wearing full CBRN and laser protective clothing. If full CBRN protective clothing is not worn by the aircrew, then the Aircraft shall be equipped with a system capable of supplying suitably pressurized and filtered air to the crew such that the crew are properly protected against the effects of CBRN hazards (CW agent liquid and vapor, BW agent in the form of aerosol and nuclear hazards in the form of dust). Appropriate levels of protection are required for the eyes, the skin, and the nasal tract". The top-down approach to NBC defense, as depicted in Figure 4, delineates a strategy centered on key principles: avoidance, decontamination, and protection [47].

NBC avoidance entails the utilization of stand-off or remotely located detectors that can interface with the aircraft, enabling the identification of potential threats and facilitating the selection of alternate flight paths to evade contamination. Decontamination procedures involve exposing aircraft components to contaminants during flight in an NBC environment, followed by thorough decontamination using specialized solutions upon landing. In contrast, protection involves designing aircraft components to withstand exposure to NBC agents during flight, obviating the need for post-mission decontamination on the ground. Various methods, including individual, collective, and hybrid approaches, are employed for protection against NBC threats. Since aircraft crew and avionics are exposed to the NBC agents through ECS, the system-level design provides extensive protection against the NBC agents.

Individual protection necessitates the use of specialized equipment, including a respiratory system and a protective suit [48]. For respiratory protection in aircraft applications, M40 masks are commonly utilized, offering comprehensive protection for the respiratory tract, eyes, and face against NBC agents. These masks feature an elastic head harness, binocular eye lenses, front and side voice meters, and a filter canister [49]. Similarly, the mission-oriented protective posture (MOPP) serves as the designated protective suit against NBC agents, comprising an overgarment, hood, mask, over boots, and gloves [50].

However, individual protection poses significant risks to both avionics and crew health. While crew members are safeguarded, avionics remain vulnerable to NBC threats and must undergo subsequent decontamination, necessitating meticulous precautions during maintenance procedures. Moreover, wearing protective equipment during flight can induce discomfort and potential hazards for crew members, including inaccurate fitting of equipment, overheating, and slipping of respirators on sweaty faces [51].

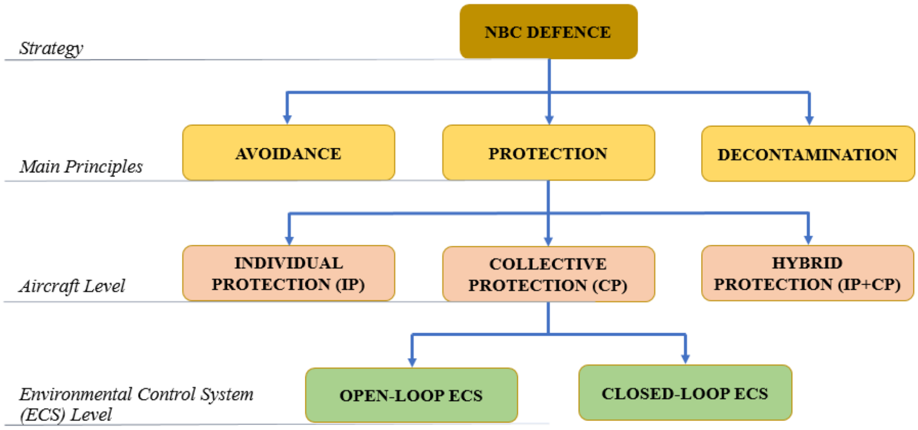

Fig. 4. Top Down Approach for NBC Defense [24]

In addition, the study [52] has shown that protective mask and clothing with significant weight usually decrease the time to sustain a particular activity level. Individual protection equipment may cause overheating in the body. It is estimated that the body temperature increases by 5°C for personnel in an NBC protection suit [53]. Many studies on the human thermal response [54-62] have demonstrated that the humans can tolerate a 630J heat load at a body temperature of 40°C. Exceeding this limit can lead the body to collapse. Furthermore, the degradation in mental performance, such as impairment in judgment, occurs at body temperatures below that limit. Thus, the crew cannot recognize his or her involvement in a dangerous situation [63].

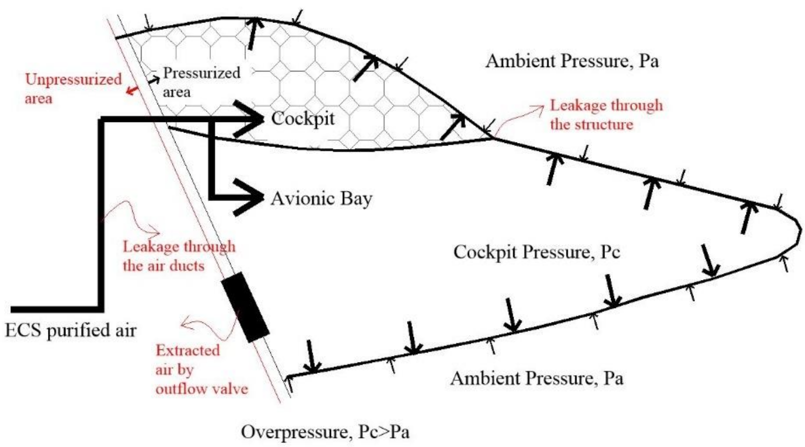

Fig. 5. Schematic of Overpressure in Aircraft [64]

In contrast, collective protection offers a more comprehensive protection mechanism. The collective protection in aircraft points to overpressure system, which is the build-up of purified air in the aircraft, as shown in Figure 5. ECS supplies purified or filtered air to crew and avionic bay, ensuring a comfortable environment and the cooling of avionics, respectively. Outflow valves discharge a portion of the supplied air outside to maintain pressure within the cockpit within safe limits. Additionally, some air leakage occurs through the aircraft's structure and air supply ducts passing through unpressurized compartments. The air leakage may be estimated using the Eq (1) [65]:

$$W_D = 123 \times P_C \times Z \times CA / \sqrt{T_C} \quad (1)$$

where,W_D: Estimated leakage rate (lbs./min), P_C: Cabin pressure (psia), Z: Function of pressure ratio between cabin and ambient and it is between 0,53 and 1 and it is taken 0,256 for the pressure ratios equal to 0,53 and lower than 0,53, CA: Equivalent leakage area, (in^2), T_C:Cabin temperature (^{o}R).Z, the function of pressure ratio between cabin and ambient in Equation (1), is calculated with pressure values of ambient and cabin and specific air heat ratio in Equation (2).

$$Z = \sqrt{\left(\frac{P_A}{P_C}\right)^{2/k} - \left(\frac{P_A}{P_C}\right)^{(k+1)/k}} \quad (2)$$

where, P_C: Cabin pressure (psia), P_A: Ambient pressure (psia), k: Air specific heat ratio, c_p/c_v.

The structure, doors, windows, air ducts, and other openings within an aircraft are meticulously designed to ensure an air-tight seal, minimizing any potential leakage. The volume of air supplied by the Environmental Control System (ECS) exceeds the combined amount of discharged air and air leakage, thereby maintaining a positive pressure differential within the aircraft compared to the contaminated external environment. This positive pressure creates an overpressure environment, effectively preventing the infiltration of contaminated air into the aircraft during NBC scenarios. As a result, both crew members and avionics can operate without the need for stringent individual protection equipment, thereby mitigating the risk of contamination [24].

The ECS is engineered with the concept of either an open-loop configuration or partial closed-loop configurations, facilitating the establishment of overpressure and collective protection within the aircraft. Alongside these configurations, a third concept, the closed-loop configuration, is employed solely for the cooling of the cockpit and avionics. In this setup, air is not drawn from the external environment but instead continuously recirculated, refrigerated, and utilized for cooling purposes within the cockpit and avionics compartments, as illustrated in Figure 6. However, since maintaining overpressure in the cockpit necessitates compensating for air leakage, the closed-loop ECS configuration may not be suitable. Therefore, this article focuses on the partial closed-loop configuration over the closed-loop option.

In the partial closed-loop ECS configuration, engine bleed air is drawn into the system, where it undergoes refrigeration to cool the cockpit and avionic components. The cooled air is then recirculated within the system, as illustrated in Figure 8. The system draws additional engine air if necessary to compensate for any leakage and to replenish oxygen levels.

In open-loop configuration, the source for supply air is usually engine bleed air over the flight. ECS continually gathers engine bleed air, subjecting it to refrigeration, and subsequently employs it to cool the cabin, cockpit, and avionics, as depicted in Figure 7. Collective NBC protection necessitates the ECS's design to have certain prerequisites, including hardening, air-tight construction, and filtering, to guarantee that any degradation will not occur in the system over its entire operation in an NBC environment.

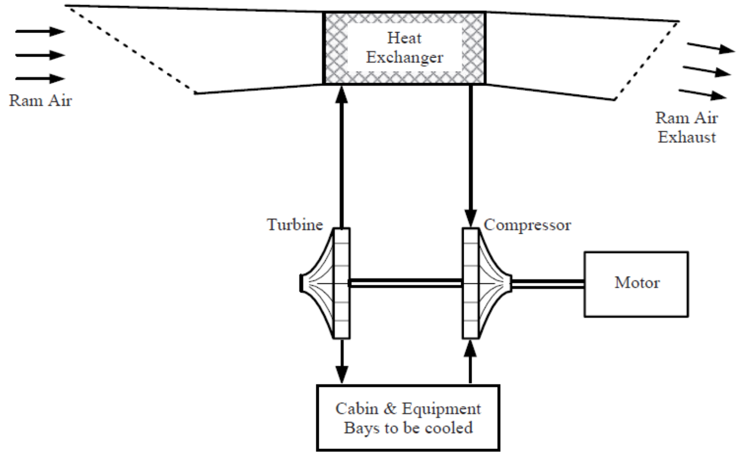

Fig. 6. Configuration of Closed-loop ECS [66]

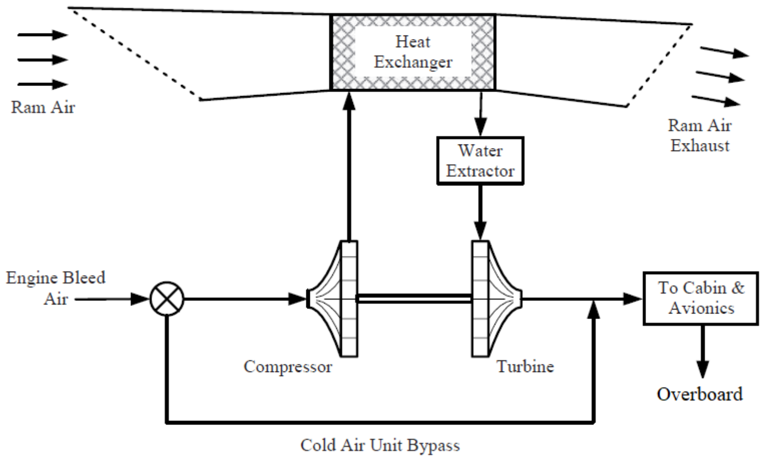

Fig. 7. Configuration of Open-loop ECS [66]

ECS needs the hardening requirements to have resistance to the nuclear, biological, and chemical agents using the approved NBC-resistant materials and design without any structural or functional degradation. Material selection is critical, with emphasis on minimizing the outgassing rate - the gradual release of trapped, dissolved, or absorbed gas from materials under extreme pressure and temperature conditions [67, 68]. Low pressure and high temperature are the proper conditions to trigger the outgassing phenomena. The buildup of the outgassed products causes the enclosed environment to be hazardous to the crew when the allowable limit is exceeded. Moreover, particles released by outgassing may interfere with the avionics and may degrade avionics' performance in the aircraft. Therefore, material selection with respect to outgassing rate is one of the control methods to reduce the quantity of toxic products in aircraft. Materials like solvents, resins, adhesives, and polymers are more susceptible to outgassing phenomena, while metals are the least susceptible to it. The molecular structure defines the susceptibility to the outgassing. A material is less susceptible to outgassing if it is more compact and stable when subjected to extreme environmental conditions. In addition to material selection, the design of hardening methods plays a crucial role in NBC protection.

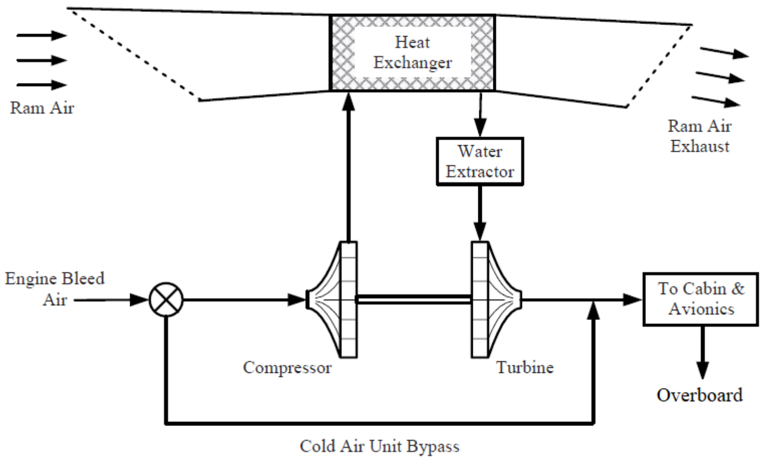

Fig. 8. Configuration of Partial Closed-loop ECS [66]

Recommended hardening practices for the ECS include sealing lapped surfaces, fasteners, and recesses around fastener heads, as well as shielding electrical connectors [24].Most of the military ECS designs allow cockpit cooling air to flow through the avionics to provide forced cooling to the air-cooled avionics. Therefore, contaminated cooling air may threaten the avionics. At least the following practices are recommended to diminish the impacts of the contaminants on the avionics:

- Drain holes are removed if possible.
- All printed circuit boards have a conformal coating, a protective thin polymeric film such as acrylic, epoxy, silicone, polyurethane, polyester, and perylene [69-71]. It is recommended to provide the coating with the thickness as shown in Table 4.
- The cold plate design is integrated into the avionics to eliminate the contact of contaminated cooling air with the electronic components. A cold plate is a heat exchanger that takes the heat released from the electronic component via heat conduction [73].

Table 4. Recommended Thickness of Polymerics for Conformal Coating [72]

Type of Coating	Thickness (inch)
Acrylic, Epoxy, and Polyurethane	0.002 ± 0.001
Silicone	0.005 ± 0.003
Parylene	0.0006 ± 0.0001

Ensuring air-tightness is paramount for aircraft when implementing collective NBC protection measures [74]. To achieve this, controlling leakage through sealing is recommended. The efficacy of a seal relies on the properties of both the constructed material and the materials it interacts with, thereby providing dependable sealing. When selecting seals, factors such as temperature, pressure, manufacturing method, sealed fluid, and application locations should be carefully considered [75]. It is imperative to choose seal types and materials resistant to NBC agents, considering their specific strengths and limitations, and aligning them with the application locations to prevent the ingress of NBC agents into the aircraft, as outlined in Table 5. Additionally, components of the ECS exposed to ultraviolet light and ozone should possess resistance to prevent seal failure.

Table 5. Typical Sealing Mechanisms on ECS Components for NBC Protection [76-78]

NBC Agents' Ingress Route	Requirements for Seals	Recommended Seals
Bleed air	- Resistance to high temperature (300-600ºC). - Resistance to high pressure (20-50psi). - Withstand vibration. - Resistance to chemical agents (oil, hydraulic fluids, etc.).	Metal-elastomer seal with a backup O-ring
Air inlet/outlets	- Resistance to chemical agents. - Resistance to corrosion.	Labyrinth seal with NBC-resistant materials
Air ducts' joints, connections, and access panel	- Resistance to chemical agents. - Withstand vibration.	O-ring seals or gaskets with NBC-resistant materials
Air filters	- Resistance to chemical agents. - Resistance to high and low temperatures. - Resistance to pressure differentials.	O-ring seals or gaskets with NBC-resistant materials
Valves	- Compensating for axial, lateral, and angular movements in the valve. - Resistance to chemical agents, corrosion. - Resistance to pressure differentials, high and low tempeatures, and vibration.	Diaphragm seals, bellows seals.
Heat exchangers	- Resistance to chemical agents. - Resistance to high and low temperatures. - Resistance to pressure differentials.	Gaskets, flanges, and O-rings with NBC-resistant materials

Seal materials such as fluorinated and butyl rubbers usually resist the NBC agents. On the other hand, silicone, polyolefins, polysulfides, and Buna-N materials easily sorb the agents due to their porous atomic structure [24]. Therefore, they are not the best materials for the seals in the overall NBC protection. Air filtering is another requirement in the collective NBC protection since it separates the contaminants from the air supplied to the pressurized compartments. There are three main concepts of NBC filters namely non-regenerable, agent destruction, and regenerable filters as illustrated in Figure 9.

Non-regenerable filters are low-pressure and high-pressure carbon filters, which are based on the use of activated carbon bed technology. They consist of a high-efficiency particulate filter (HEPA) and carbon adsorption bed, as shown in Figure 10. Contaminated air passes through the HEPA filter in which at least 99.97% of aerosol particles (solid and liquid) with a size of 0.3 microns or larger hold, including bacteria and viruses. In other words, The HEPA filter's size limits its ability to completely remove aerosol particles smaller than 0.3μm. Filters no longer meet the specification requirements since their "removal effectiveness" gradually decreases during operation, necessitating their regular replacement [79]. Besides, the HEPA filter has a limitation that does not remove gaseous contaminants or volatile organic compounds. For this reason, an activated carbon bed is attached to a HEPA filter to hold the contaminated molecules on the surface with the principle of adsorption method.

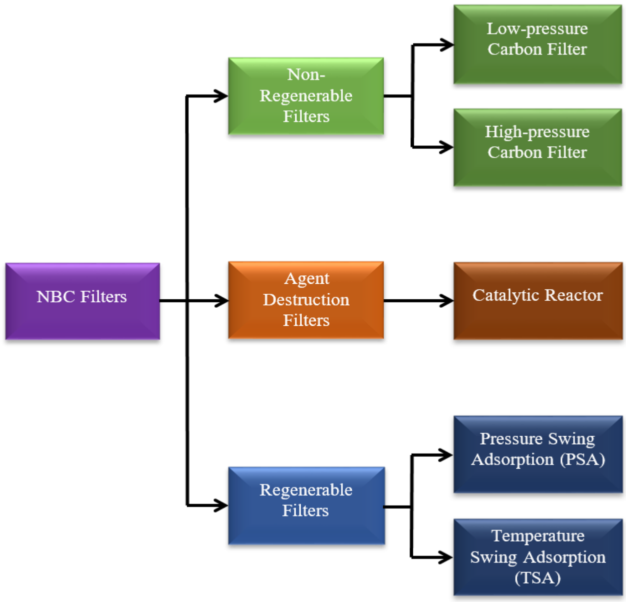

Fig. 9. Tree Diagram of Concepts of NBC Filters [24]

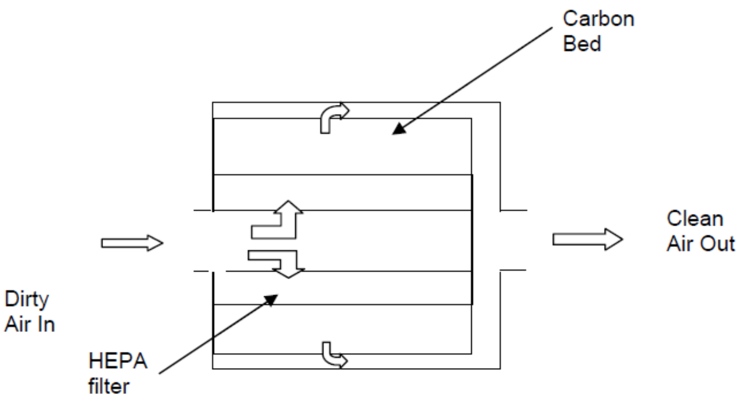

Fig. 10. Illustration of a Typical Carbon Filter [24]

The filter still has some limitations, as follows:

- It may not hold the contaminant particles of which the size is smaller than 0.3 microns.
- It may not provide a high level of protection against chemicals with vapor pressure between 10 mmHg and 100 mmHg. Furthermore, it will certainly not provide a significant protection against the chemicals with vapor pressure higher than 100 mmHg [80].
- It must be replaced when dirty, which may cause a logistical burden.
- There is a concern that new chemical agents, called, as carbon breakers, fall outside the protection capability of carbon filters.

Another type of NBC filter, the agent destruction filter, works with the catalytic oxidation method. It removes the contaminants through a chemical reaction between them and the catalyst. In Figure 11, bleed air is preheated to the ideal temperature for the oxidation reaction. Then, heated air is directed to the catalyst bed which has a metal catalyst that promotes the oxidation of contaminant agents. A catalyst is not altered since it is usually stable and made of specialized materials such as platinum or palladium [81]. The oxidation breaks down the agents into less harmful byproducts such as carbon dioxide and water. Finally, it comes to the post-treatment filter, which prevents fine particles not completely oxidized during the catalytic process.

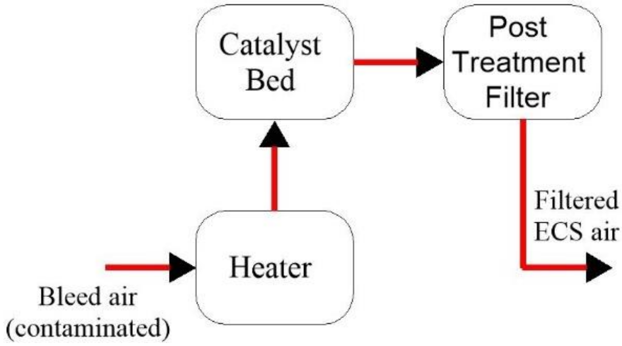

Fig. 11. Illustration of a Typical Catalytic Oxidation System [24]

The last type of NBC filters is the regenerable filter. It has sorption technologies based on pressure swing adsorption (PSA) and temperature swing adsorption (TSA) methods. A typical PSA system used two beds for adsorption, one is online, and the other is offline. It has three steps for each bed in the cycle: production, depressurization, and purge, as shown in Figure 12.

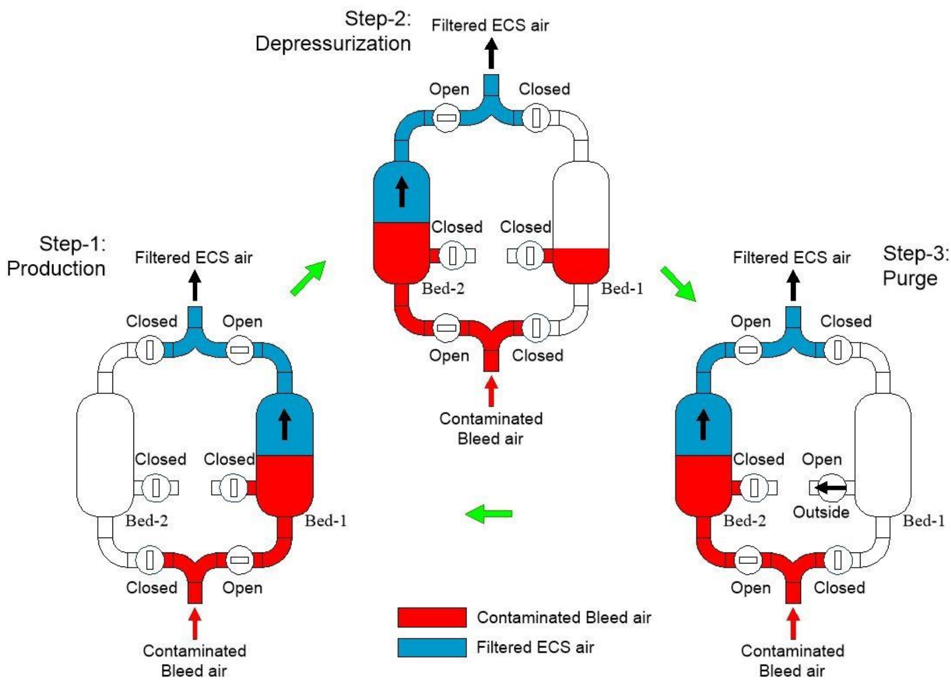

Fig. 12. Illustration of a Typical PSA cycle [82]

Step 1, which is production, involves a supply of contaminated air from the outside to the bed-1 (vessel) containing an adsorbent in high pressure. High pressure keeps the contaminants on the surface of the adsorbent; the purified air is fed to the cockpit. When the bed-1 is full of contaminated air, the air supply is directed to the bed-2 in Step-2 which is depressurization. The inlet and outlet lines of the bed-1 are closed, and the pressure inside the vessel decreases prior to the purge. When the pressure is decreased in the vessel, the contaminants held on the surface are released and exhausted to the outside by the purge valve in Step 3, which is purge. These three steps repeat themselves in a loop based on the pressure change in the vessel which is called the pressure swing method. TSA uses a similar method with PSA except that it is based on temperature cycles instead of pressure cycles.

In an open-loop configuration, ECS continuously draws air from external sources, primarily through the engine bleed port [83]. Subsequently, it filters the air, refrigerates it, distributes it to pressurized compartments, and eventually discharges it overboard [84, 85]. Given that bleed air originates from the ambient environment, it may contain contaminants if the aircraft is operating within an NBC environment. Consequently, it is imperative to decontaminate the bleed air before supplying it to the cockpit and avionics bay. Although high temperatures (ranging from 400 to 650°C for the high-pressure stage) encountered in the engine bleed air can eliminate certain NBC contaminants, some may still bypass this process due to short dwell times in the bleed air system [24]. To address this, NBC filters are installed along the conditioned bleed air lines before supplying air to the cockpit and avionics bay, as depicted in Figure 13. This approach, known as "Clean Cockpit and Clean Avionics Bays," ensures effective NBC protection [24].

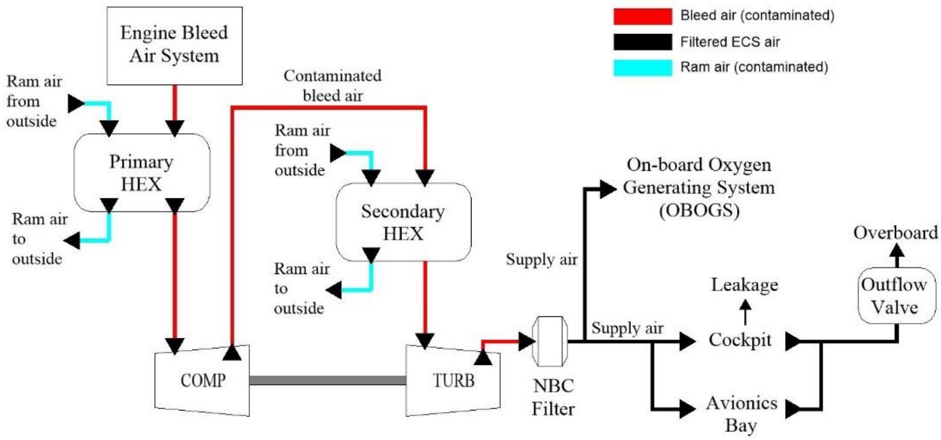

Fig. 13. Illustration of an Open-Loop ECS Configuration with NBC Filter [64]

In a more prevalent configuration, the NBC filter is positioned downstream of the compressor, ensuring purified air is supplied to both the cockpit and the avionics bay. However, in this setup, ECS components located upstream of the NBC filter may be vulnerable to contamination risks. To mitigate this, decontamination procedures can be implemented for the components situated upstream of the NBC filter on the ground, thus mitigating the risk of contamination. Alternatively, positioning the NBC filter upstream of the compressor can provide enhanced protection, albeit requiring stringent qualification standards for the filter to operate reliably, including resistance to high temperatures and pressures. Nonetheless, this placement may potentially compromise the compressor's performance due to significant pressure reduction caused by the NBC filter.

In contrast to the open-loop ECS configuration, the partial closed-loop ECS configuration does not continually draw bleed air. Instead, it draws air once and recirculates it within the cockpit, reducing reliance on bleed air [86]. Compensating for air leakage from pressurized compartments, excess air dump through outflow valves, and supplying air to the oxygen generating system is achieved through bleed air supply, as illustrated in Figure 14. NBC filters are strategically positioned upstream of the ECS mixing manifold to eliminate contaminants before the air is supplied to compartments and other customer services such as On-Board Oxygen Generating Systems (OBOGS). Additional filters may be incorporated into the cockpit recirculation airline if deemed necessary.

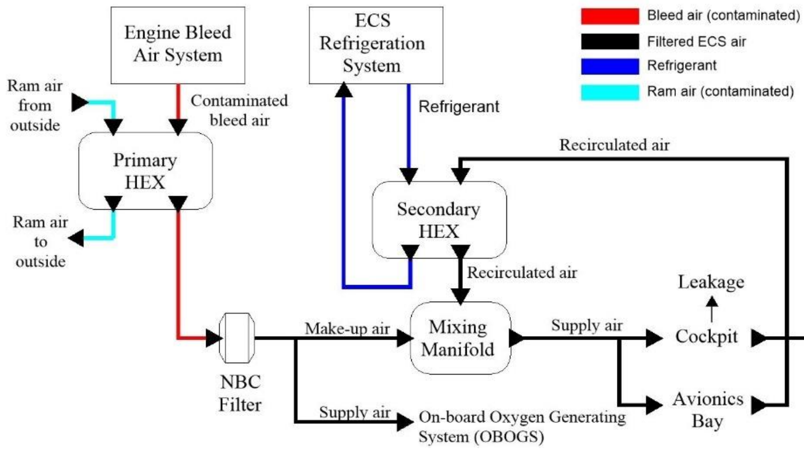

Fig. 14. Illustration of a Partial Closed-Loop ECS Configuration with NBC Filter [64]

It is crucial to carefully consider the selection of ECS configuration, considering various factors such as aircraft capabilities, mission duration, mission risk, and the required level of NBC protection. Different configurations offer distinct advantages in ensuring a safe environment within the aircraft, as summarized in Table 6.

Aircraft limitations, including ECS weight, power budget, and installation area, must be considered. In this context, the open-loop ECS configuration typically proves to be a more suitable solution for small aircraft, whereas the partial closed-loop ECS configuration offers comprehensive NBC protection for larger aircraft.

Mission duration is another critical parameter influencing ECS configuration selection for NBC protection. For short-duration missions with acceptable risk levels, the open-loop ECS configuration may suffice, as NBC effects on the aircraft are typically brief. Conversely, for longer missions where the risk of NBC contamination is higher, the partial closed-loop ECS configuration is recommended to provide enhanced protection.

The sizing of the NBC filter is determined by the flow rate of contaminated air passing through it. In the open-loop ECS configuration, the filter must be sized to accommodate all outside air supplied to the cockpit, while in the partial closed-loop ECS configuration, it is sized only for the make-up air flow rate since air circulates within the cockpit. Additionally, the open-loop configuration is more prone to filter saturation due to higher contaminant concentrations, increasing maintenance workload and risk. Maintenance requirements thus play a crucial role in ECS configuration selection.

In terms of NBC contamination exposure, the open-loop ECS exposes the cockpit air directly to NBC contaminants, as it filters all outside air. In contrast, the partial closed-loop configuration limits direct contact with contaminants, as air circulates within the cockpit, with contact occurring only when make-up air is required.

Table 6. Comparison of open-loop and partial closed-loop ECS configurations

Parameter *	Open-loop ECS configuration	Partial Closed-loop ECS configuration
Aircraft capability	Fit to small aircraft	Fit to larger aircraft
Mission's duration	Fit to the short missions	Fit to the longer missions
NBC risk	Fit to the missions with low NBC risk	Fit to the missions with high NBC risk
Filter Capacity	All air	Make-up air
Filter Failure	Higher possibility of filter saturation due to the high concentration of the contaminants	Lower possibility of filter clogging
Maintenance workload	Higher due to a higher risk of contamination	Lower due to lower risk of contamination
Contaminated air	All air direct contact with contaminated air has a higher risk of contamination.	Make-up air direct contact with contaminated air lowers the risk of contamination.

*: Parameters are selected considering the health risk due to contamination. Performance and cost parameters, such as bleed air penalty, weight, noise, fuel consumption, complexity, and cost, are not considered since they may depend on the specific information from the aircraft's manufacturer or component's supplier.

3. Conclusions

Collective NBC protection in military aircraft offers significant advantages by eliminating the need for individual NBC protection equipment, thereby enhancing crew safety and operational efficiency. This approach not only safeguards crew members from the discomfort and potential risks associated with individual protective gear but also ensures the integrity of avionics systems by obviating the need for post-flight decontamination.

To optimize the effectiveness of collective NBC protection, key design concepts such as hardening, air-tight construction, and advanced filtering mechanisms must be incorporated into the Environmental Control System (ECS). These features enable the ECS to maintain full operational capability throughout the entirety of a mission in an NBC environment, without degradation.

Furthermore, the selection between open-loop and partial closed-loop ECS configurations should be based on careful consideration of aircraft capabilities, mission duration, risk factors, and the desired level of protection. While open-loop ECS offers advantages in terms of weight, power, and installation area constraints, it provides less comprehensive protection compared to partial closed-loop ECS, particularly during extended missions where the risk of NBC contamination is higher.

The size and maintenance requirements of NBC filters are directly influenced by airflow rates, with open-loop ECS necessitating larger filters due to the filtration of all outside air. However, partial closed-loop ECS configurations require smaller filters, as they only filter make-up air. Additionally, the risk of filter saturation and failure is mitigated in partial closed-loop ECS, reducing maintenance workload and enhancing overall system reliability.

Ultimately, the adoption of a partial closed-loop ECS configuration presents a lower risk of contamination throughout the duration of a flight, as recirculated air remains isolated from NBC contaminants. By carefully considering these factors and implementing appropriate design strategies, military aircraft can ensure robust collective NBC protection while maintaining operational flexibility and efficiency.The findings of this review present a wealth of opportunities for future research and development in the realm of collective NBC protection for military aircraft. Building upon the insights gleaned from this study, researchers can delve deeper into several areas ripe for exploration.

Firstly, further investigations could focus on refining and optimizing the design concepts of hardening, air-tight construction, and filtering within ECS systems to ensure uninterrupted operational capability throughout extended durations in NBC environments. By honing these design elements, future studies can strive to enhance the effectiveness and reliability of collective NBC protection measures.

Moreover, there is a pressing need for research into the development of advanced ECS configurations that strike a delicate balance between protection efficacy and resource constraints. Studies could delve into exploring innovative approaches to ECS design, considering factors such as aircraft capabilities, mission duration, and risk levels to tailor solutions that maximize protection while minimizing associated burdens on weight, power, and installation space. Additionally, investigations into the performance and durability of NBC filters within ECS systems warrant attention. Future studies may seek to optimize filter sizing and airflow rates to mitigate the risk of premature saturation and failure, thereby reducing maintenance workload and enhancing overall system reliability.

Furthermore, comparative studies between open-loop and partial closed-loop ECS configurations could provide valuable insights into the trade-offs between protection levels and operational constraints. By systematically evaluating the performance and effectiveness of these configurations under various mission scenarios, researchers can inform decision-making processes regarding ECS selection and deployment strategies.

Overall, the outcomes of this review serve as a catalyst for further inquiry and innovation in the field of collective NBC protection for military aircraft. Through collaborative efforts and interdisciplinary research endeavors, the potential exists to propel advancements that safeguard both crew and aircraft against the evolving threats of NBC contamination.

Nomenclature

ABC	Atomic, biological, and chemical
CBRN	Chemical, biological, radiological, and nuclear
ECS	Environmental control system
EMACC	European military airworthiness certification criteria
HEPA	High-efficiency particulate filter
MOPP	Mission-oriented protective posture
NBC	Nuclear, biological, and chemical
OBOGS	On-board oxygen generating system
PSA	Pressure swing adsorption
TSA	Temperature swing adsorption

References

[1] European Commission Joint Research Centre (JRC). Chemical, biological, radiological and nuclear hazards. [Internet]. [cited 2024 Jan 16]. Available from: [https://commission.europa.eu/about-european-commission/departments-and-executive-agencies/joint-research-centre_en].

[2] Robinson JP, editor. The Routledge Handbook of Nuclear, Biological and Chemical Weapons. Routledge; 2009.
[3] Oppenheimer A, editor. Jane's nuclear, biological and chemical defence 2010-2011. Jane's Information Group; 2010.
[4] Garrett BC, Hart J. Historical dictionary of nuclear, biological, and chemical warfare. Lanham, MD: Scarecrow Press; 2007.
[5] Federal Office for Civil Protection (FOCP). The NBC Protection. [Internet]. [cited 2024 Jan 16]. Available from: [https://www.nccs.admin.ch/nccs/en/home/the-nccs/about-the-nccs/organisation/members-and-partners/federal-office-for-civil-protection-FOCP.html]
[6] U.S. Army. NBC Decontamination. [Internet]. [cited 2024 Jan 16]. Available from: [https://www.army.mil/]
[7] Clements BW. Nuclear and radiological disasters. In: Disasters and public health. Elsevier; 2023. p. 211-236. https://doi.org/10.1016/B978-1-85617-612-5.00014-7
[8]National Aeronautics and Space Administration. Introduction to the Electromagnetic Spectrum. NASA Science. [Internet]. [cited 2024 Jan 16]. Available from: [https://science.nasa.gov/ems/01_intro/].
[9] Morton H, Johnson C. Chemical, biological, radiological and nuclear major incidents. Surgery (Oxford). 2021;39(7):416-422. https://doi.org/10.1016/j.mpsur.2021.05.005
[10] U.S. Department of the Army. Field Manual 8-9. U.S. Government Printing Office; 1996.
[11] National Environment Agency. Radiation basics. [Internet]. Available from: https://www.nea.gov.sg/our-services/radiation-safety/understanding-radiation/radiation-basics. Last accessed: 16 January 2024.
[12]Motchenbacher CD, Connelly JA. Low-noise electronic system design. Wiley Interscience; 1993. ISBN: 0-471-57742-1.
[13] Adams GE, Smith TD. The effects of radiation on electronic systems. Springer Netherlands; 1981.
[14] Berger HW. Radiation effects in semiconductors. CRC Press; 2000.
[15] Messenger SR. Single-event effects in integrated circuits. Springer Science & Business Media; 2004.
[16] Dodd PE, Masuda M, Virtanen A. Radiation hardening techniques for emerging technologies. Nature Electronics. 2022;5(4):268-281. doi:10.1038/s41928-022-00804-y.
[17] Saltmarsh RB. Nuclear radiation effects on electronic components. In: Macdonald JR, editor. Radiation effects in electronics. CRC Press; 1999; 215-275.
[18] Murgai VS. Radiation effects in semiconductor devices. In: Hamamatsu HC, Sawaki N, editors. Radiation effects on semiconductors. Springer Netherlands; 2001. p. 217-240.
[19] Lanford WA. Ionizing radiation effects on materials and devices. In: Macdonald JR, Freeman WT, editors. Radiation effects in electronics. CRC Press; 2007; 277-317.
[20] Solovyev AV. Protection of electronic systems from nuclear radiation. Springer-Verlag New York Inc; 2011.
[21] Bulinski AT, Petrenko AA. Radiation hardening of electronics. CRC Press; 2013.
[22] Saalbach KP. Biological warfare. In: Schaechter M, editor. Encyclopedia of microbiology. 4th ed. Elsevier; 2019. p. 520-525. https://doi.org/10.1016/B978-0-12-801238-3.62160-8
[23] Shuvo II, Dolez PI. Design of a military protective suit against biological agents. In: Hu F, Miao J, editors. The Textile Institute Book Series. Academic Press; 2023; 141-176. https://doi.org/10.1016/B978-0-323-91593-9.00009-2
[24] Society of Automotive Engineers. NBC Protection Considerations for ECS design (SAE AIR 4362A). 2014.
[25] Aly MA. Biocontamination of Avionics: A Review of Current Knowledge and Future Directions. MDPI; 2018.
[26] Patel KK. Biological effects on avionics and aircraft systems. Springer Nature; 2020.

[27] Chen CH. Protecting avionics from biological threats: A comprehensive guide. InTech; 2021.
[28] Smith JJ. Biological contamination of avionics: Prevention, detection, and response. CRC Press; 2022.
[29] Ali NA. The challenges and opportunities of protecting avionics from biological agents. Frontiers. 2023.
[30] U.S. Department of the Army. Chemical, biological, radiological, and nuclear platoons (ATP 3-11.74). 2011.
[31] Fletcher CD. Effects of ionizing radiation on living tissues. Oxford University Press; 1997.
[32] Narayanan VR. Biological Effects of Radiation. Elsevier; 2008.
[33] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The health effects of radiation exposure. United Nations; 2020.
[34] Murray PR, Rosenthal KS, Pfaller MA. Medical microbiology. 9th ed. Elsevier; 2020.
[35] Russell DA. The anthrax handbook. Springer-Verlag New York Inc; 2003.
[36] Luchansky DB. Botulinum Neurotoxins. Marcel Dekker Inc; 2000.
[37] Gupta RC. Handbook of toxicology of chemical warfare agents. Academic Press; 2009.
[38] Wilkinson TC. Chemical warfare agents: Toxicology and treatment. Medical Chemical Publishing; 2004.
[39] Sidell FR, Goodman EH, Willson TD, editors. Medical aspects of chemical warfare. Office of the Surgeon General, U.S. Army Medical Department, Center for Countermeasures; 2009.
[40] The International Federation of Red Cross and Red Crescent Societies (IFRC). Chemical, biological, radiological and nuclear (CBRN) hazards; 2022.
[41] Bland SA. Chemical, Biological, Radiological and Nuclear (CBRN) Casualty Management Principles. In: Conflict and Catastrophe Medicine. Springer; 2013. p. 747-770. https://doi.org/10.1007/978-1-4471-2927-1_46
[42] Doran BM. The Human and Environmental Effects of CBRN Weapons [Student Theses, Fordham University]. Fordham Research Commons; 2015.
[43] Klare MT. The Next Great Arms Race. Foreign Affairs. 1993;72(3):136–152. https://doi.org/10.2307/20045628
[44] Department of Defense. Airworthiness Certification Criteria (MIL-HDBK-516C); 2014.
[45] European Defence Agency. European Military Airworthiness Certification Criteria (EMACC); 2018.
[46] U.K. Ministry of Defence. Certification Specifications for Airworthiness Part 13: Military Common Fit Equipment (00-970); 2020.
[47] Zahradníček R, Otřísal P, Skaličan Z. CBRN consequence management: New approach and possibilities of participation of chemical units. Security and Defence Quarterly. 2016;10(1):147-163. https://doi.org/10.5604/23008741.1215432
[48] U.S. Department of Army. Field Manual: NATO Handbook on the Medical Aspects of NBC Defensive Operations (FM 8-9). U.S. Army Medical Department; 1996.
[49] U.S. Department of Army. Field Manual: NBC Protection (FM 3-4/11-9). U.S. Army Medical Department; 1992.
[50] U.S. Department of Army. Field Manual: Multiservice Tactics, Techniques, and Procedures for Nuclear, Biological, and Chemical (NBC) Protection (FM 3-11.4). U.S. Army Medical Department; 2003.
[51] Janssen L, Johnson AT, Johnson JS. Chemical, Biological, Radiological, and Nuclear (CBRN) Respiratory Protection Handbook. National Institute for Occupational Safety and Health; 2018.
[52] Johnson AT, et al. Respirator masks protect health but impact performance: a review. Journal of Biological Engineering. 2016;10(1):125-136. https://doi.org/10.1186/s13036-016-0025-4
[53] Department of Defense. Human Engineering (MIL-STD-1472G); 2012.

[54] Buchberg H, Harrah CB. Conduction Cooling of the Human Body - A Biothermal Analysis. In: Thermal Problems in Biotechnology. ASME Symposium Series; 1968. p. 82-95.
[55] Cole RD. Heat Stroke During Training with Nuclear, Biological and Chemical protective Clothing: Case Report. Military Medicine. 1983;148(7):624-625. doi:10.1093/milmed/148.7.624. https://doi.org/10.1093/milmed/148.7.624
[56] Fanger PO, Nevins RG, McNall PE. Predicted and Measured Heat Losses and Thermal Comfort Conditions for Human Beings. In: Thermal Problems in Biotechnology. Winter Annual Meeting of the ASME; 1968. p. 111-126.
[57] Harrison MH, Higenbottam C. Heat Stress in an Aircraft Cockpit During Ground Standby. Aviation, Space, and Environmental Medicine. 1977;48(6):519-523.
[58] Hwang CL, Konz SA. Engineering Models of the Human Thermoregulatory System- A Review. IEEE Transactions on Biomedical Engineering. 1977;24(4):309-25. https://doi.org/10.1109/TBME.1977.326137
[59] Stribley R, Nunneley SA. Physiological requirements for design of environmental control systems: Control of heat stress in high performance aircraft. ASME Paper presented at the Intersociety Conference on Environmental Systems (78-ENAS-22); 1978. p. 1-8.
[60] Wing JF. Upper Thermal Tolerance Limits for Unimpaired Mental Performance. Aerospace Medicine. 1965;36(10):960-964.
[61] Wissler EH. Mathematical Simulation of Human Thermal Behavior Using Whole Body Models. In: Heat Transfer in Medicine and Biology. Springer, New York, NY; 1985. p. 325-374.
[62] Shender BS. Predictions of Human Tolerance to Heat Stress While Wearing Advanced Integrated Suit Concepts During Simulated Realistic Combat Scenarios. Naval Air Warfare Center, Aircraft Division Warminster Report No. NAWCADWAR-94136-60; 1993.
[63] Johnson AT. Biomechanics and exercise physiology: quantitative modeling. Boca Raton, FL: Taylor & Francis; 2007. https://doi.org/10.1201/b15850
[64] Güler E. Compliance Strategy for the Certification of Environmental Control System in Military Applications. Mühendis ve Makina; 2024. https://doi.org/10.46399/muhendismakina.1257053
[65] Society of Automotive Engineers Standard. Airplane Cabin Pressurization (SAE ARP 367C); 1963.
[66] Moir I, Seabridge A. Environmental control systems. In: Aircraft systems. 3rd ed. John Wiley & Sons; 2022. p. 259-295.
[67] Pedley MD. Materials and Processes Branch. In: Safety Design for Space Systems. Elsevier; 2023. p. 401-420. https://doi.org/10.1016/B978-0-323-95654-3.00028-6
[68] National Aeronautics and Space Administration (NASA) Standard. Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion (NASA STD 6001); 1998.
[69] Society of Automotive Engineers Standard. Conformal Coatings for Panels, Printed Circuit and Panels, Electronic Circuit
[70] Snedeker KG, Pike TW. Electronic circuit protection technology. CRC Press; 1984.
[71] Haba M. Conformal coating technology for improved circuit reliability. TT Electronics; 2018.
[72] Department of Defense. Insulating Compound, Electrical (For Coating Printed Circuit Assemblies). (MIL-I-46058C); 1966.
[73] Society of Automotive Engineers Standard. Cooling of Military Avionic Equipment (SAE AIR 1277B); 2005.
[74] Department of Defense. CB Collective Protection of Mobile Vehicles, Vans and Shelters (MIL-HDBK-753); 1971.
[75] Ernsberger RR, editor. Handbook of seals and sealing. Elsevier; 2014.

[76] Anderson JD Jr, Raymer JC. Aerospace Engineering. McGraw-Hill Education; 2014.
[77] Sauter R, Shevell WS. Aircraft Environmental Control Systems. American Institute of Aeronautics and Astronautics; 2012.
[78] Boer ER, Schijve JL. Aerospace seals: A handbook for design and engineering. Elsevier; 2011.
[79] Saraçyakupoğlu T. Major Units and Systems in Aircraft. In: Kuşhan MC, Gürgen S, Sofuoğlu MA, editors. Materials, Structures and Manufacturing for Aircraft. Sustainable Aviation. Springer; 2022. https://doi.org/10.1007/978-3-030-91873-6_10
[80]Morrison RW. NBC Filter Performance. U.S. Army Soldier and Biological Chemical Command; 2001. https://doi.org/10.21236/ADA397007
[81] Tarraf M, Soltan M, Elweteedy A. Gas Phase Air Cleaning Using Catalytic Oxidation. In: International Conference on Aerospace Sciences and Aviation Technology; 2013. https://doi.org/10.21608/asat.2013.22271
[82] Singh B, Singh VV, Boopathi M, Shah D. Pressure swing adsorption based air filtration/purification systems for NBC collective protection. Defence Life Science Journal. 2016;01(2): https://doi.org/10.14429/dlsj.1.10737
[83] Society of Automotive Engineers Standard. SAE Aerospace Applied Thermodynamics Manual Aerothermodynamic Systems Engineering and Design (SAE AIR 1168-3A); 2019.
[84] Giorgi L. Design of Innovative Environmental Control Systems for high-speed commercial aviation [Master's thesis]. The University of Politecnico di Torino Research Repository; 2019.
[85] Poudel S. Modelling of a Generic Aircraft Environmental Control System in Modelica [Master's thesis]. Diva Portal Research Repository, Linköping University; 2019.
[86] Edgar JM, Campbell B. Evaluation and Control of an Integrated Closed Environmental Control System (ICECS). SAE Transactions. 1990;99:545–560. https://doi.org/10.4271/901237