



## COMPLIANCE STRATEGY FOR THE CERTIFICATION OF ENVIRONMENTAL CONTROL SYSTEM IN MILITARY APPLICATIONS

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### Keywords

*Certification, environmental control system, means of compliance, military standard, safety*

### Abstract

*This review paper provides the compliance strategy for the certification activity of environmental control systems (ECS) according to the military standard. Firstly, the paper defines the ECS. Secondly, it outlines the steps for the system's certification activities in the concept of the means of compliance. Thirdly, it recommends the minimum set of documents with technical explanations obtained by academic learning, vocational training and recommendations from the regulations for compliance with the given requirements in military certification of ECS. Then, the differences in terms of compliance methods are specified. Finally, it is concluded that a specific compliance strategy for military certification of ECS is required for a systematic and comprehensive approach.*

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## ÇEVRESEL KONTROL SİSTEMİ'NİN ASKERİ UYGULAMALARA ÖZEL UÇUŞA ELVERİŞLİLİK SERTİFİKASYONUNA İLİŞKİN UYUM DOĞRULAMA STRATEJİSİ

### Anahtar Kelimeler

### Öz

*Sertifikasyon, çevresel kontrol sistemi, uyum doğrulama metodu, askeri standart, emniyet*

*Bu makale, çevresel kontrol sistemlerinin (ECS) askeri standartlara göre sertifikasyonu için uyum doğrulama stratejisi sağlayan derleme bir yayındır. Makalede ilk olarak çevresel kontrol sistemi tanımlanmış, ikinci olarak, uyum doğrulama metotları kapsamında, sistem sertifikasyon süreci ana hatlarıyla sunulmuştur. Daha sonra çevresel kontrol sistemlerinin askeri sertifikasyonu için önerilen minimum gereksinim doğrulama dokümanları, akademik bilgiler ile iş tecrübeleri ve yönetmelik tavsiyeleri göz önüne alınarak teknik açıklamaları ile birlikte verilmiş, uyum doğrulama metotlarındaki farklılıklar ortaya konmuştur. Son olarak ise, ECS özelinde sistematik ve geniş kapsamlı bir askeri sertifikasyon süreci için spesifik bir uyum doğrulama veri seti sunulmuştur*

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## 1. Introduction

Aircraft is a large-scale and complex vehicle consisting of multiple systems to function throughout its flight envelope. ECS is one of the aircraft systems that provides pilots not only a comfortable environment but also a safe environment since it is related to human activities.

ECS is the system associated mainly with ventilation, air conditioning, and pressurization in occupied compartments for safe and comfortable flight (Parsons, 1999). It also provides pressurized bleed air to critical safety air customer systems such as canopy seal, defog, anti-g, and oxygen systems.

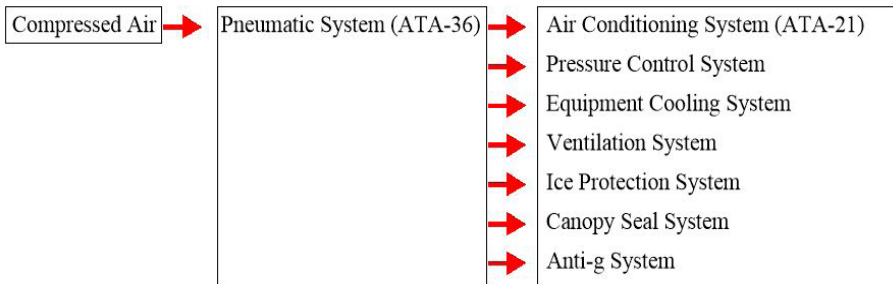


Figure 1. Environmental Control System (Sarçyakupoglu, 2020)

The main ECS functions in military applications are presented as follows:

- Supply pressurized bleed air to air cycle machine (ACM) consisting of compressor and turbine.
- Supply conditioned air to the cockpit to provide the pilot comfortable environmental conditions throughout the flight envelope.
- Provide cooling energy to avionics, especially the safety-critical ones.
- Provide air to critical interfacing systems such as on-board oxygen generating systems (OBOGS) and anti-g systems.
- Supply heated air to the windshield for defog and anti-icing/de-icing capability for extensive and clear visibility.
- Provide smoke evacuation in the cockpit when required.
- Provide air to the canopy seal system.
- Provide radar pressurization.
- Monitor, detect, and alert the bleed air leakage.

- Provide fuel efficiency (An efficiently designed ECS contributes to fuel savings by optimizing temperature distribution and reducing the load on the aircraft power systems.)

Military aircraft typically do not circulate cabin air which is exhausted overboard. It usually has one pack. A typical system architecture is illustrated in Figure 2.

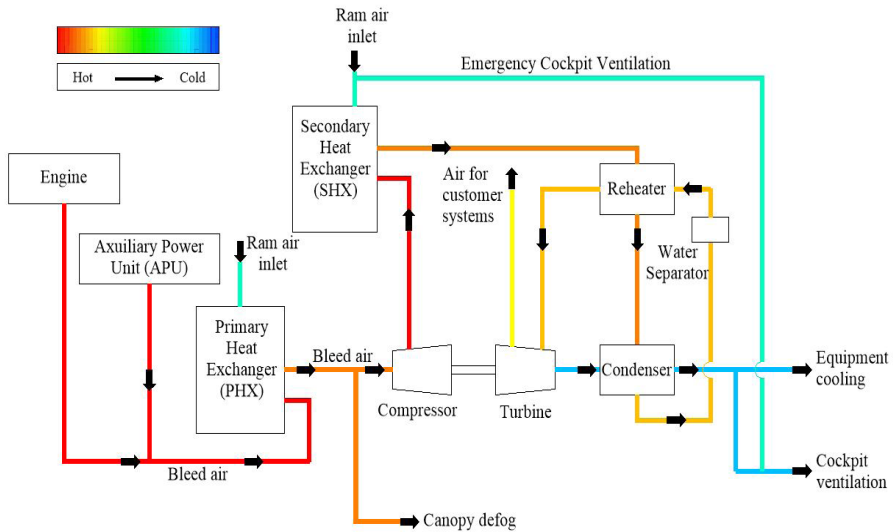


Figure 2. Typical ECS Schematic for Military Applications (The figure was re-illustrated based on the information (Chowdhury, Ali & Jennions, 2023))

ECS takes pressurized bleed air from the powerplant or pressurized air from ground support equipment (GSE). Bleed air then passes through the primary heat exchanger (PHX), and its temperature drops to a certain range to get efficient performance from the compressor. It also branches to a defog line to supply relatively hot air to the canopy to provide a sufficiently extensive view for safe operation when required.

The air passes through the compressor which is one of the main components of air cycle machine (ACM). While passing through it, the pressure of air increases, so the temperature does. The high temperature due to compression decreases again with the help of a secondary heat exchanger (SHX). A condenser which is downstream of SHX provides air to drop its moisture by cooling it. A water separator (WS) is designed to extract water droplets from the air. The turbine's blades may get damaged since the frozen the water droplets may hit the turbine

blades with high rotational speeds (Yang, Yuan, Kong, Zheng & Li, 2022). The air drops some of its water content. However, it may still be in the condensation temperature zone. A reheater is placed just at downstream of the water separator. It heats the air to escape the condensation temperature zone to prevent any more condensation before passing through the turbine. Air finally goes through the turbine. Its temperature decreases to a certain range to supply the cockpit and/or equipment cooling. Some air is directed to critical safety air customer systems such as anti-g, on-board oxygen generating, and canopy seal systems.

ECS is an essential and safety-critical system in military aircraft since it serves to pilot and flight critical equipment. It also provides air to the safety critical systems such as the anti-g system, oxygen generating system, and canopy seal system. ECS may face the following failures that can put the flight in a catastrophic failure condition:

- Bleed air contamination,
- Bleed air leakage,
- Pressurization failure,
- ECS supply failure to critical systems such as OBOGS and anti-g systems,
- Smoke evacuation failure in the cockpit,
- Partial or total loss of cooling for flight-critical avionics,
- Loss of windshield defog capability,
- Loss of windshield anti-icing or deicing capabilities,
- ECS supply failure to canopy seal,

Since there are many serious failure conditions, necessary safety precautions are required within the design. It is expected to comply with the safety requirements for the airworthiness certification of ECS. Certification is the legal recognition that the applicant with its organization, service, and product complies with the directives of the regulations as illustrated in Figure 3(SAE Standard, 1996).

This paper focuses on only the certification of the applicant's product, which consists of many complex systems such as landing gear, mechanical, propulsion, avionics, etc. Those systems, including ECS are subject to certification activities. A plan is prepared to manage the certification activities with a systematic approach. Therefore, certification planning provides a division of overall regulation into manageable task in a systematic manner (SAE Standard, 1996).

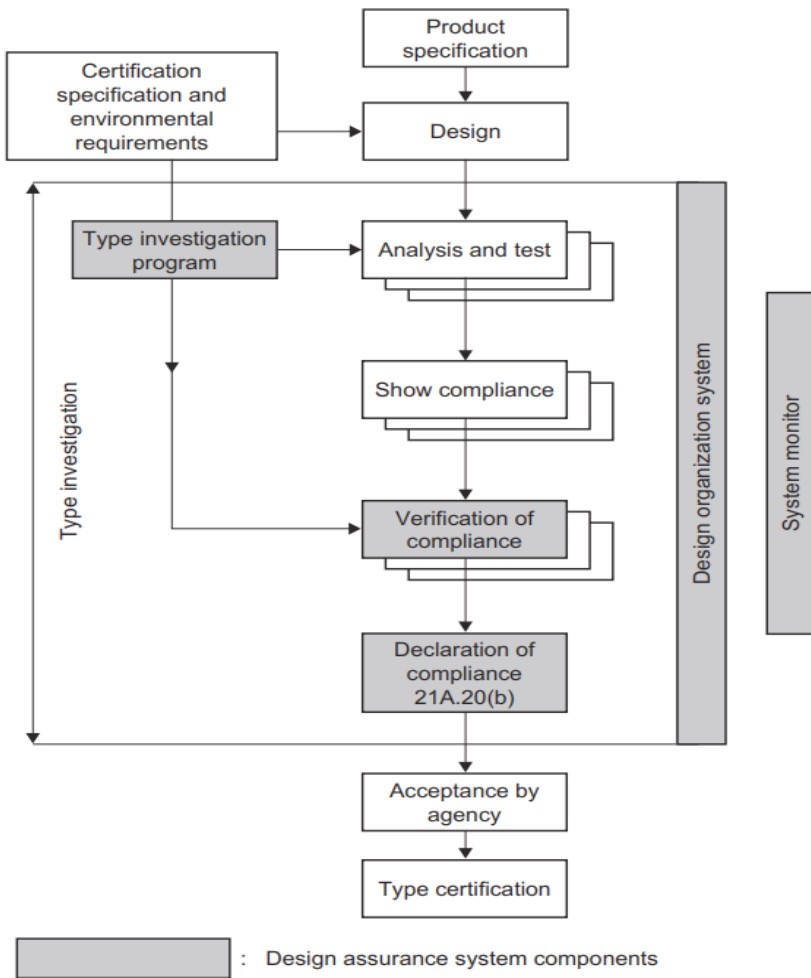


Figure 3. Relationship between Design, Design Assurance, and Type Investigation (Florio, 2006)

The project certification plan defines the certification basis, which outlines the applicable set of standards according to the regulations. Since military aircraft has many systems, more than one certification plan may be prepared and dedicated to the system’s response to decrease complexity and workload. ECS certification plan is one of those separate plans and includes system definition, applicable requirements, compliance methods and documents at least. There are many means of compliance (compliance method) and proof of compliance (associated compliance document), as found in Table 1.

Table 1. Means of Compliance Codes (European Union Aviation Safety Agency Regulation, 2021)

Type of compliance	Means of Compliance (MC) #	Associated Compliance Documents
Engineering evaluation	MC0: - Compliance statement - Reference to design data - Election of methods, factors, etc. - definitions	- Design data - Recorded statements
	MC1: design review	- Descriptions - Drawings
	MC2: calculation/analysis	- Substantiation reports
	MC3: safety assessment	- Safety analysis
	MC4: laboratory tests	
Tests	MC5: ground tests on related product(s)	- Test programs - Test reports
	MC6: flight tests	- Test interpretations
	MC8: simulation	
Inspection	MC7: design inspection/audit	- Inspection or audit reports
Equipment qualification	MC9: equipment qualification	Note: Equipment qualification is a process that may include all previous means of compliance at the equipment level.

Since there are many means of compliance for the system’s certification verification, a systematic approach is necessary not to skip any document for compliance with the applicable requirements. A compliance strategy document is beneficial in this aspect, including;

- The applicable requirements are based on certification basis,
- Methods of compliance that satisfies the safety requirements given in the regulation.
- Proof of compliance to cover all technical data to show that the minimum required safety level is provided for the system.

In civil aviation, International Civil Aviation Organization (ICAO) is a global organization that has regulations and recommendations to provide safety requi-

rements for civil aviation (Purton & Kourousis, 2014; Purton, Clothier & Kourousis, 2014; Saraçyakupoğlu, 2022) It is also commonly known as Chicago Convention(International Civil Aviation Organization Regulation, 2006). There is a statement in ICAO such as “this convention shall be applicable only to civil aircraft and shall not be applicable to state aircraft”(Purton, Clothier & Kourousis, 2014; Saraçyakupoğlu, 2022; ICAO, 2006). State aircraft is defined as aircraft designed for special purposes for countries’ own benefits, such as military aircraft.

In military aviation, there is no international organization like ICAO. That means there is no global set of regulations for military applications which have higher level of safety risks. There are many safety regulations and guidelines in military applications for the applicant who is responsible for showing compliance to the applicable airworthiness regulations (Ashforth & Ilcewicz, 2017). MIL-HDBK-516C is one of the regulations used for the purpose of ECS’s airworthiness certification in military applications. It is strong in providing high level system requirements in a qualitative manner for guidance. However, it is not clear in the debate between applicants and authorities which are necessary to give a rationale for certification judgments (Linling, Wenjin & Kelly, 2011). This paper intends to develop a compliance strategy to make an explicit justification in terms of means of compliance and to provide a systematic approach to airworthiness certification activities of ECS in military applications.

It is considered that this study may be beneficial within the military aerospace industry, including all shareholders such as design, engineering, maintenance, state military aviation authorities, airworthiness specialists, and manufacturers.

This study is complied with research and publication ethics.

## **2. ECS Compliance Methods For The Applicable Requirements From MIL-HDBK-516C**

MIL-HDBK-516C has criteria, standards, and compliance means to guide the applicant in certification activities. This chapter takes the criterion from MIL-HDBK-516C as it is. Then, the compliance methods and its technical explanations from all applicable military regulations and vocational experience are expressed as the study on the compliance for each requirement.

### **2.1 Design for Safety**

Criterion as it has been stated in the standard: “Verify that the design incorporates the system safety requirements of the air vehicle” (DoD Standard, 2014).

The safety design approach includes at least the following items (Kritzinger, 2006; DoD Standard, 1993; DoD Standard, 2013) :



- Design for minimizing risk,
- Safety devices,
- Warning devices,
- Training,
- Redundancy,
- Independency,
- Fail-safe mechanism,
- Fault tolerance.

These items about safety design should be included in the system description document (SDD). Details for the items mentioned above should be carefully considered for effective risk management.

Besides, the routine and emergency operating procedures for all operations are also reviewed for ECS's design integration with aircraft in safety. Therefore, it had better submit the manuals for the flight and the maintenance as compliance documents.

System safety assessment (SSA) defines the functional hazard cases to provide incorporation of safety requirements into the functions. Failure mode and effect analysis are used to examine failure situations and recommend safety designs and procedures as illustrated in Table 2.

Table 2. Sample of Failure Mode and Effect Analysis (SAE Standard, 1996)

FAILURE MODE AND EFFECTS ANALYSIS (FMEA) - Sample for pressure regulating and shut-off valve (PRSOV) pressure sensor							
System: ECS			FMEA Description: Loss of indication of PRSOV outlet pressure				Date:
Subsystem: Air Conditioning			Author:				
Item ATA: ATA-21			FTA References:				Rev:
Function Names	Function Code	Failure Mode	Mode Failure Rate	Flight Phase	Failure Effect	Detection Method	Comments
Pressure Sensor	-	Loss of indication	1,00E-05	All	Loss of ECS Supply	ECS Controller	

Flight test confirms the performance of the environmental control system and

other connected systems involving thermal stability for flight safety (DoD Standard, 2014).

The means of compliance with the requirement are MC1, MC3, MC5, and MC6.

## 2.2 Integration

Criterion as it has been stated in the standard: “Verify that the ECS meets safety requirements when operating under intended conditions over the design envelope and maintains integration integrity to ensure the weapon system’s safety of flight” (DoD Standard, 2014).

This chapter differs from the chapter “Design for Safety” since it focuses on meeting safety requirements of operational conditions.

System safety assessment document (SSA) confirms that the ECS does not have negative effect on the flight safety. Quantitative analysis in SSA helps to get target failure rates that flow from the aircraft level to ECS component level. Components are required to be designed according to the target failure rates given in SSA.

The equipment qualification form of which a sample is illustrated in Table 3, shows that the components in ECS have complied with environmental qualification and safety requirements over the operating envelope.

Table 3. Sample of Environmental Qualification Form (Federal Aviation Administration, 1993)

<b>Qualification Evidence Report - Sample</b>		
Conditions	Section	Description of tests conducted
Temperature and altitude		
Temperature variation		
Humidity		
Operational shock and crash safety		
Vibration		
Explosive atmosphere		
Waterproofness		
Fluids susceptibility		
Sand and dust		
Fungus		

Salt fog test  
Magnetic effect  
Power input  
Voltage spike  
Audio frequency susceptibility  
Induced signal susceptibility  
Radio frequency susceptibility  
Radio frequency emission  
Lighting induced transient susceptibility  
Lighting direct effects  
Icing  
Electrostatic discharge  
Fire, flammability  
Other tests

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Ground test or simulator (if possible) demonstrates ECS's safe operation over the operating envelope (DoD standard, 2014).

The flight test is the final verification method for ECS's safe operation in all operating conditions. Flight test also validates safety analysis results.

The means of compliance with the requirement are MC3, MC4 or MC5 or MC8, MC6, and MC9.

### **2.3 Alternate Cooling**

Criterion as it has been stated in the standard: "Verify the availability of alternate means of thermal conditioning of safety-critical avionics (including the control station) and sufficient cockpit ventilation when the primary ECS is nonoperational" (DoD Standard, 2014) .

The avionics need to be cooled are listed in SDD. Safety-critical avionics may be defined as mission-essential or safe return avionics (DoD Standard, 2013). Design approach may be defined for the alternate cooling, such as ram air design for air-cooled equipment and liquid cooling design for liquid cooled avionics.

An appropriate level of redundancy and independence are the factors that should be analyzed carefully in case of a failure in cooling system components. In the failure condition of the cooling system, the safety-critical avionics are expected to continue their operation without cooling over a required time period.

Thermal performance for safety-critical avionics is calculated with thermal analysis. This helps to comply with cooling requirements regarding avionics' thermal stability.

MIL-HDBK-516C recommends conducting a ground test. However, the ground test may not be an appropriate method to analyze safe return or mission completion concepts. Instead, flight test can be conducted for more accurate results.

The flight test demonstrates that enough cooling exists for the safety-critical avionics considering flow rate and temperature distributions along the avionics. The flight test is conducted in hot, cold, warm, and dry atmospheric conditions. It is advantageous to have avionics close to the end product. However, the prototype may give close results for the test. The cooling system is tested to verify that the temperature for avionics remains in the specified operational range (SAE Standard, 2015). However, flight tests should be reconsidered since they may be risky if safety-critical avionics cannot operate.

The means of compliance with the requirement are MC1, MC2, and MC6.

## 2.4 Pressurization

Criterion as it has been stated in the standard: "Verify that normal and emergency pressurization requirements are met in the air vehicle system and, as appropriate, are indicated or monitored at the control station to ensure safety of flight" (DoD Standard, 2014).

The pressure schedule is determined for pilot comfort and aircraft safety. It is controlled by a cabin pressurization control system (CPCS) which precludes rapid changes in cabin pressure (Sathiyaseelan & Selvan, 2022; DoD Standard, 1998). The rapid pressure change may cause aviation diseases such as barotrauma and decompression sickness (DoD Standard, 2015; Auten, Kuhne, Walker & Porter, 2010). Hypoxia may be another disease due to improper operation of CPCS (Sathiyaseelan, 2014). It is required to have coordination with oxygen system designers to confirm that the crew has appropriate environment for breathing. A common schedule is applied to prevent such undesired conditions. A typical CPCS schedule is illustrated in Figure 4.

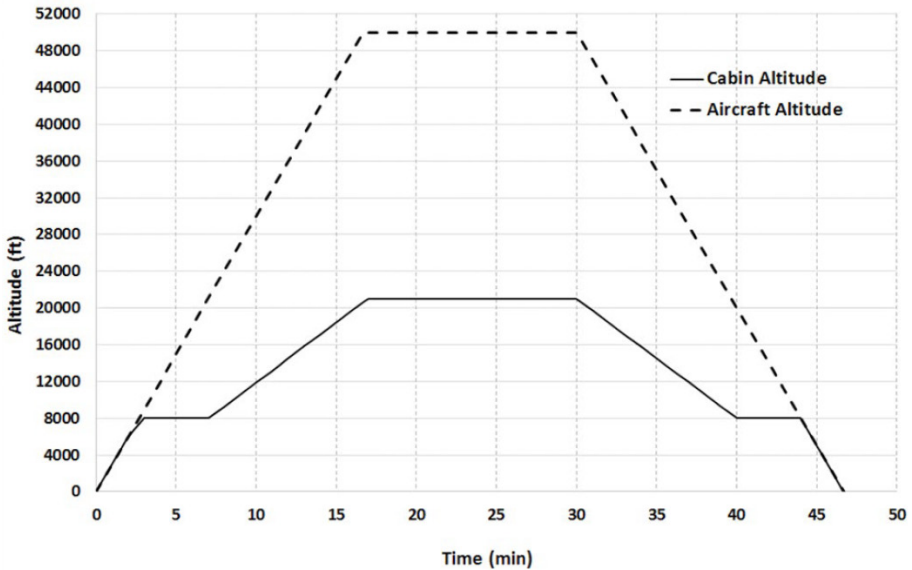


Figure 4. Typical CPCS Schedule (Pleil, 2017; Arunachalam & Varadappan, 2023)

The pressure schedule should be demonstrated in SDD to verify that the pressure design is within safe limits.

Analyses and/or simulations show the needs for cockpit’s pressurization. The adequacy of pressurization system is confirmed with the capability analysis (DoD Standard, 2014).

Laboratory tests provide a chance to evaluate interaction between regulators before the flight test (DoD Standard, 2013). However, the laboratory cannot simulate the whole system. Therefore, flight tests are necessary to show the final compliance including all operating conditions.

Flight test verifies the appropriate operation of the pressurization system. Although a flight test is usually preferred for verification, the analysis may be sufficient in case safety cannot be provided in verification activity in flight, such as the failure of the pressurization system.

The means of compliance with the requirement are MC1, MC2, MC6, and MC9.

## 2.5 Degraded System Operation

Criterion as it has been stated in the standard: “Verify that the effects of loss of some or all ECS functions on air vehicle system safety and performance are understood and acceptable” ((DoD Standard, 2014) .

Loss of some or all ECS functioning may cause interfaced systems to operate in a degraded mode. Onboard oxygen system generating system, anti-g system, and canopy seal system that require pressurized supply air are highly sensitive to degradation of ECS functions. Safety-critical avionics is another system that has an interface with ECS and needs cooling energy from ECS. SDD defines the continuous operation of safety-critical avionics in all ECS's failure scenarios. Safety critical components are required to have function to land safely in case of all possible ECS failure scenarios.

The structural integrity is required to be provided for the rotating equipment in ECS. Equipment manufacturer needs to show that components of all rotating equipment are contained so that parts resulting from the failure of rotating equipment do not cause any negative effect on system safety.

SSA verifies the air vehicle system's safe operation and acceptable performance after losing some or all ECS functions. It is recommended to check that the failure risks of ECS are within the safe limits at first hand.

The means of compliance with the requirement are MC1, MC3, and MC9 according to Table 1.

## **2.6 Technical Manuals**

Criterion as it has been stated in the standard: "Verify that normal and emergency operating procedures, limitations, restrictions, servicing, and maintenance information are included in the flight and maintenance manuals and training curriculum" (DoD Standard, 2014) .

Aircraft flight manual (AFM), aircraft maintenance manual (AMM), and training curriculum are delivered to confirm that necessary instructions of which a sample is presented in Figure 5, are provided to ensure the safe operations under all operating conditions including emergency over the flight envelope.

**COCKPIT PRESSURE/TEMPERATURE MALFUNCTION**

Loss of cockpit pressurization could be caused by canopy seal, air-conditioning system, or cockpit pressure regulator safety valve malfunctions or ECS shutdown or failure.

Certain ECS equipment malfunctions result in temporary shutdown of the ECS. These shutdowns are more prevalent at high altitude during low speed flight with high engine thrust settings. An ECS shutdown is characterized by an oily, smokey smell, followed by loss of cockpit noise and airflow and gradual loss of pressurization. These temporary shutdowns typically last from 20-45 seconds or, on occasion, up to 2 minutes. The EQUIP HOT caution light may illuminate if the shutdown lasts longer than 20 seconds.

**WARNING**

With the ECS shut down or the AIR SOURCE knob in OFF or RAM, the g-suit does not inflate **6D** and PBG is disabled.

Most AUTO position temperature failures can be corrected by use of the MAN position.

If cockpit pressure altitude exceeds **6E** 22,500, **LESS** **6E** 27,000 feet, the CABIN PRESS caution light illuminates.

If the cockpit temperature is excessive and does not respond to AUTO or MAN temperature commands or cockpit pressure is lost, proceed as follows:

1. OXYGEN – 100%.
2. Altitude – 25,000 feet maximum.
3. Airspeed – 500 knots maximum.
4. AIR SOURCE knob – OFF (10-15 seconds), then NORM.

If cockpit pressure is not regained but all other systems dependent on the ECS are operational:

5. Flight may be continued below 25,000 feet.

If ECS has failed or cockpit temperature control is not regained:

5. AIR SOURCE knob – OFF.
6. AIR SOURCE knob – RAM (after cockpit is depressurized).

**NOTE**

External fuel cannot be transferred in OFF or RAM. Consider jettisoning tanks to decrease drag if range is critical and ECS cannot be turned on for short periods of time to transfer fuel.

7. Nonessential electrical equipment – Off.

**NOTE**

If in VMC and the ADI and HSI are not required for flight, the INS should be considered nonessential.

8. Land as soon as practical.
9. Check for failed essential dc bus(es). Refer to EMERGENCY POWER DISTRIBUTION, this section.

Figure 5. Sample of ECS Directive in F-16A Aircraft Flight Manual (DoD Standard, 2003)

The environment is getting contaminated over time. The build-up of contamination in ECS may cause partial or total loss of ECS functions. Therefore, a health monitoring system can provide updated health data about ECS's critical components, such as heat exchangers, to the maintenance crew to prevent failures. Hence, conditioned maintenance may also be considered with scheduled maintenance (Fellague, Nwadiogbu, Menon, Borghese & Patankar, 2012; Hare, Gupta, Najjar, D'Orlando & Walthall, 2015). It is recommended to check data about conditioned maintenance in AMM to preclude any unexpected failure of components that are highly sensitive to contaminated environments.

The means of compliance with the requirement are MC1.

## 2.7 Operator Interface

Criterion as it has been stated in the standard: “Verify that adequate controls and displays for the environmental control system are installed in the crew station/control station or other appropriate locations to allow the environmental control system to function as intended” (DoD Standard, 2014) .

In the study about human factors in aircraft accidents (Australian Transport Safety Bureau, 1996), over 70% of flight information is received by the pilot’s eyes. Another study stated that human factors cause more than 80% of flight accidents (Kamaleshaiah & Guruprasad, 2022). This underlines the importance of human-centered design to reduce accidents sourced from pilot’s workload. In the aspect of human-centered design, ergonomics analysis is recommended to verify that the pilot’s workload is acceptable (EASA Regulation, 2023).

ECS and crew system specialists should be in coordination to show compliance with the requirement. Appropriate caution and warning indicators are necessary to alert the crew to act on time without any injury or increased workload in case of failure in ECS. The locations of caution and warning indicators should also be carefully designed considering minimum head and eye movements according to the pilot’s visual fields as illustrated in Figure 6.

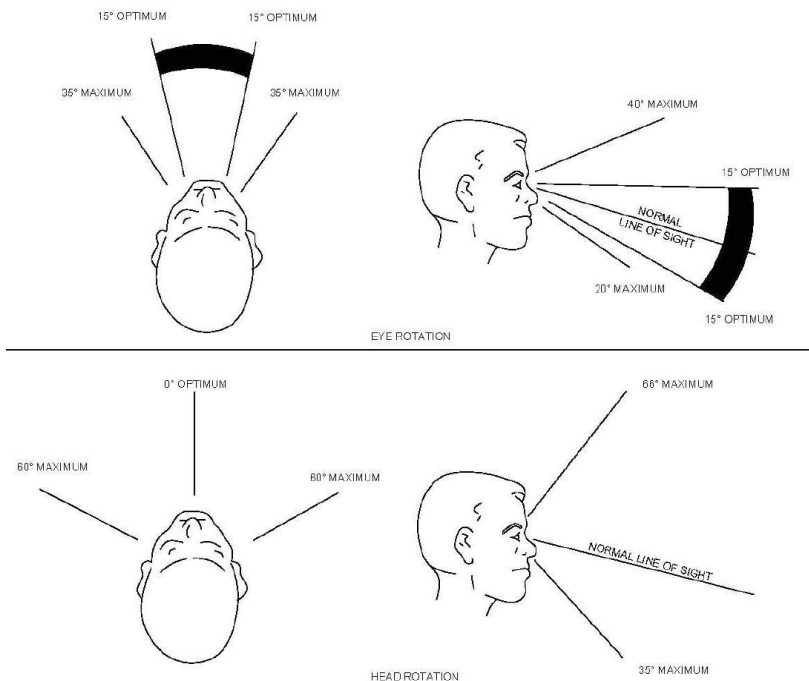


Figure 6. Eye and Head Rotations for a Pilot (DoD Standard, 2012)



Inspection of drawings including ECS control items confirms that the required control, cautions, advisories, and warnings are incorporated (DoD Standard, 2013). This would be an indication, control and advisory system (ICAS) installation plan.

Failure analysis may provide a benefit for checking the error conditions in ECS monitoring system. The safety design approach regarding redundancy or independence may be studied if error condition in the monitoring system has a higher probability than expected. Such design approaches should be included in SSA for mitigation if required.

Crew station mockup is used to verify adequate controls and displays for ECS.

Qualification tests conducted in laboratory provide safe and relatively inexpensive method to test possible failure scenarios and an initial assessment of the control precision. It can identify problems in the early development stages to save money and time. Besides, it provides an environment where risky conditions can be simulated rather than executed in flight tests.

Flight test gives the last confirmation that the system complies with the requirements. It is the only method to substantiate the performance under all conditions including transients.

The means of compliance with the requirement are MC1, MC3, MC4, MC5, and MC6.

## **2.8 Personnel Accommodation**

Criterion as it has been stated in the standard: “Verify that the environmental control system meets the requirements for personnel atmosphere, including adequate crew/occupant thermal conditioning, humidity control, and ventilation; and protective flight garment supply systems (e.g., oxygen equipment, pressure suits, anti-g garments, or ventilation garments)” (DoD Standard, 2014) .

SDD defines thermal conditioning and ventilation in the cockpit and suits for the crew such as anti-g, nuclear, biological, and chemical protection (NBC) and mask. Required temperature, flow rate, and pressure levels should be designed concerning the crew’s physiological needs.

Analysis and laboratory tests provide data to show compliance with the requirements for personnel atmosphere.

SSA provides safety analysis to prove that flight safety failure rates are within tolerable limits.

Ground and flight tests substantiate the requirement. They also supply the final

approval that ECS provides a safe atmosphere to the crew over the flight envelope.

The means of compliance with the requirement are MC1, MC2, MC3, MC4, MC5, and MC6.

### 2.9 Environmental Protection

Criterion as it has been stated in the standard: “Verify that subsystems used for environmental protection (e.g., windshield rain/snow/ice removal, ice protection, and defog) provide for safe operation of the air vehicle system throughout the specified design envelope” (DoD Standard, 2014).

Ice protection and defog on a windshield can be provided by thermal, electro-thermal, electromagnetic, chemical, mechanical, and other approved methods (DoD Standard, 1985; Martínez, 1995). SDD includes methods of protection against severe environmental conditions for flight safety. The cockpit must be arranged so that the pilots have a sufficiently extensive and clear view to perform any maneuvers within the limits (EASA Regulation, 2023). It is crucial to specify the critical view area for safe operation as illustrated in Figure 7. Critical view areas should always be kept clear throughout the flight envelope.

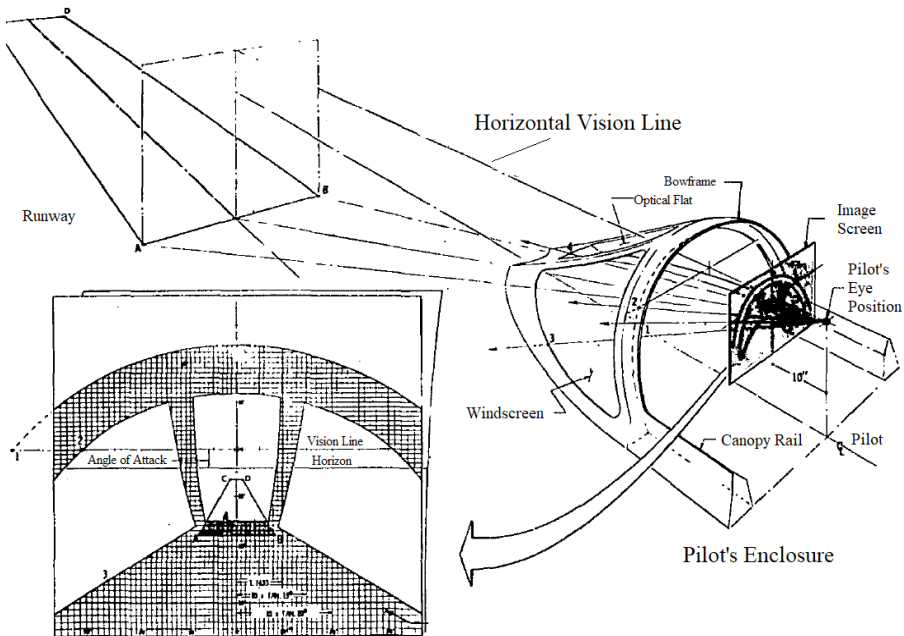


Figure 7. Pilot's External Vision Plot (DoD Standard, 1970)

Fog and ice formation on the windshield usually are cleaned with either electrical input and/or a hot air supply. The maximum temperature limit of the windshield structure should be considered not to damage the structure when heat is applied. It is recommended that temperature limit control in the hot air supply line for defog should be verified for compliance with the requirement considering the failure case in ECS.

Inlets and vents provide air transfer in ECS. Ice formation at inlets/vents disturbs air transfer, so the performance of ECS may be degraded. This may cause endanger the safety of flight. Technical analysis on inlets/vents helps the applicant to decide the severity of the environment. The applicant then decides whether these locations are ice-free or need an ice protection system (Heinrich, Ross, Zumwalt, Provorse, Padmanabhan, Thompson & Riley, 1991; Vukits & Hann, 2012). Freezing rain may cause safety problems at ECS's vents even if ice formation is tolerable and no ice protection is designed. Technical analysis will also help to decide the capacity of the system concerning the severity of the atmosphere where the aircraft operates.

SSA verifies that any environmental protection subsystem failure does not affect flight operations' safety. Provisions against fog and frost are required to be analyzed in case of a failure in ECS system. Design must show that supply to fog and frost protection is continuously available in all flight phases and failure conditions in ECS.

Critical viewing areas should be defined before ground and flight tests. Before the tests, it should be checked that the compartment is not preheated.

The means of compliance with the requirement are MC1, MC2, MC3, MC5, and MC6.

## **2.10 Personnel Air Quality**

Criterion as it has been stated in the standard: "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" (DoD Standard, 2014).

Contamination of bleed air degrades the quality of air supplied to pilot and threatens the health of the pilot in military applications.

It is referred "Contaminated Air in Aircraft" as the supplied air to the occupied space and contaminated by synthetic engine oils, hydraulic fluids, or deicing fluids (Michaelis, 2011). The contamination may occur due to oil seal failure, poor maintenance, or inefficiency in design (Chupp, Hendricks, Lattime & Steinetz, 2006; Johnson, 2018; Michaelis, 2018; Peng, Chunpin & Shuguang, 2014; The

Boeing Company, 2021). The oil may release harmful substances such as CO, CO<sub>2</sub>, and other toxic compounds for human health when exposed to high bleed air temperatures (Roth, 2015).

Ke Peng et al. (Peng, Chunpin & Shuguang, 2014) stated that half of the incidents of bleed air contamination are sourced from oil in engine or APU. Lubricant problems can occur at high speeds and temperatures in turbine engines (Johnson & Bisson, 1955). Besides, the Society of Automotive Engineers (SAE) reported that lubricant oil may leak at the engine startup or APU, at the time of transient operations and when the engine shuts down (SAE Standard, 2005). This means that even if the design is verified, air contamination may occur due to the engine's operation or APU. However, this chapter focuses on preventing bleed air contamination due to design deficiency.

In design, ECS gets pressurized air from the compressor section of the engine or auxiliary power unit during in-flight phases. Engines may have multiple compression stages to extract bleed air, such as a low-pressure port that supplies bleed air during take-off and cruise when the engine is at high power and a high-pressure port that supplies bleed air during landing when the engine is at low power (Roth, 2015).

For a standard operation scenario, the engine manufacturer should guarantee that bleed air meets the air purity requirements given in Table 4. A document including bleed air gas concentration data from the engine manufacturer should be submitted to show that substances are below the maximum allowable concentration for flight safety.

Table 4. Maximum Allowable Contaminant Concentrations (DoD Standard, 2015)

Substance	Maximum Allowable Concentration (ppm)
Acrolein	0.1
Aldehydes	1.0
Carbon Dioxide	5000.0
Carbon Monoxide	50.0
Ethanol	1000.0
Fluorine (as HF)	0.1
Hydrogen Peroxide	1.0
Methyl Alcohol	200.0
Methyl Bromide	20.0
Nitrogen Oxides	5.0

Ozone	0.1
Oil Breakdown Products	1.0
Total Remaining Hydrocarbons	250.0
Vapor Phase Water	+75°F Dew Point Maximum
Nickel	0.5 mg/m <sup>3</sup>
Cobalt	0.1 mg/m <sup>3</sup>
Submicron Particles	0.5 mg/m <sup>3</sup>

In the failure mode of the engine oil system, ECS air causes a catastrophic effect when oil leaks to the bleed air. European Aviation Safety Agency (EASA) reports that fume or smoke events are mostly associated with oil leakage in the engine or Auxiliary Power Unit (APU) (EASA Regulation, 2009). A design of a sensor measuring CO and CO<sub>2</sub> in the cockpit may be beneficial to warn the crew about the bleed air contamination. Besides, shut-off means should be provided to prevent smoke, toxic gases, or other contaminants from penetrating the pilot compartment. SDD explains the methods to provide warning and mitigation methods. In addition to SDD, SSA defines the failure conditions of shut-off means and mitigations to provide flight safety.

Nuclear, biological, and chemical substances are another source of air contamination. Therefore, NBC protection may be designed according to the assigned mission profile for the aircraft. Laboratory test conducted with simulants and live agent confirms that NBC system performs as intended. NBC protection may not be considered an airworthiness issue since it may be considered it is because of enemy aggression. However, the effects of NBC system on other systems should be considered for integration into the aircraft.

The ground test is conducted to check shut-off means to operate as designed so that contaminated air does not flow to the occupied compartment in any system failure.

Flight test verifies that air in the pilot compartment does not contain any contaminants exceeding their allowable limits.

The means of compliance with the requirement are MC1, MC3, MC4, MC5, and MC6.

### 2.11 Leak Monitoring/Detection

Criterion as it has been stated in the standard: “Verify that the bleed air or other compressed air duct system is monitored for leaks and structural integrity. Ver-

ify that hot air leaking from damaged ducting does not create an ignition source for any flammable fluids or other materials, or cause damage to safety of flight items/critical safety items” (DoD Standard, 2014).

This requirement is mainly related to Fireworthiness and Fire Protection. So, it should be analyzed with the coordination of fireworthiness and fire protection engineers. Engine bleed air’s temperature is usually higher than fuel auto-ignition temperature when the engine power is not idle. Therefore, any leakage in the bleed air duct can start a fire in the area where bleed air intersects fuel or oil lines.

Overheat detectors around the bleed air duct can detect heat when any leakage occurs as illustrated in Figure 8.

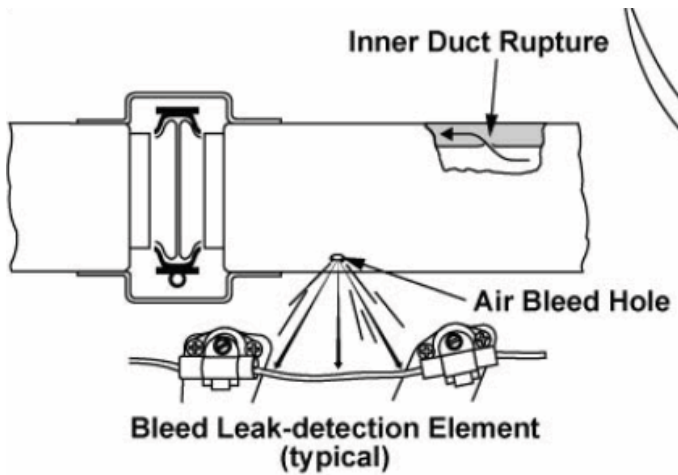


Figure 8. Typical Overheat Detector around Bleed Air Duct (The figure was re-illustrated based on the information (Majeed, 2010))

A warning alarm is initiated at the cockpit. Besides, shut-off means are necessary to make the bleed air flow stop so does the leakage. All these technical design details should be included in SDD. Inspection of SDD will provide a type of leak monitoring/detection system, and shut-off means. Inspection of drawings will provide the locations and positions of shut-off means and leak-detecting elements.

System safety hazard analysis provides the proper action items after the detection of a leakage in bleed air for the safety of flight. Quantitative analysis helps provide data showing that the bleed air duct’s failure probability is within the allowable limits.

Leakage-detecting tests may have a high risk when executing on aircraft. Therefore, a test rig may provide the benefit of verifying and validating that the leakage-detecting system operates as requested. Shut-off means may also be tested in the laboratory or even on aircraft since the on-off function is checked. The leak detector sensors should be tested in laboratory to make sure that they can operate in the desired environment and recover after disclosure to the leakage.

The means of compliance with the requirement are MC1, MC3, MC4, and MC9.

### 2.12 Bleed Air Shut-Off

Criterion as it has been stated in the standard: “Verify that bleed air shut-off provisions are available at, or as close as possible to, the bleed source” (DoD Standard, 2014).

Bleed air shut-off provisions prevent contaminants from entering the cockpit due to any probable failure in the pneumatic system. Bleed air shut-off valve is commonly used for the shut-off provision as illustrated in Figure 9.

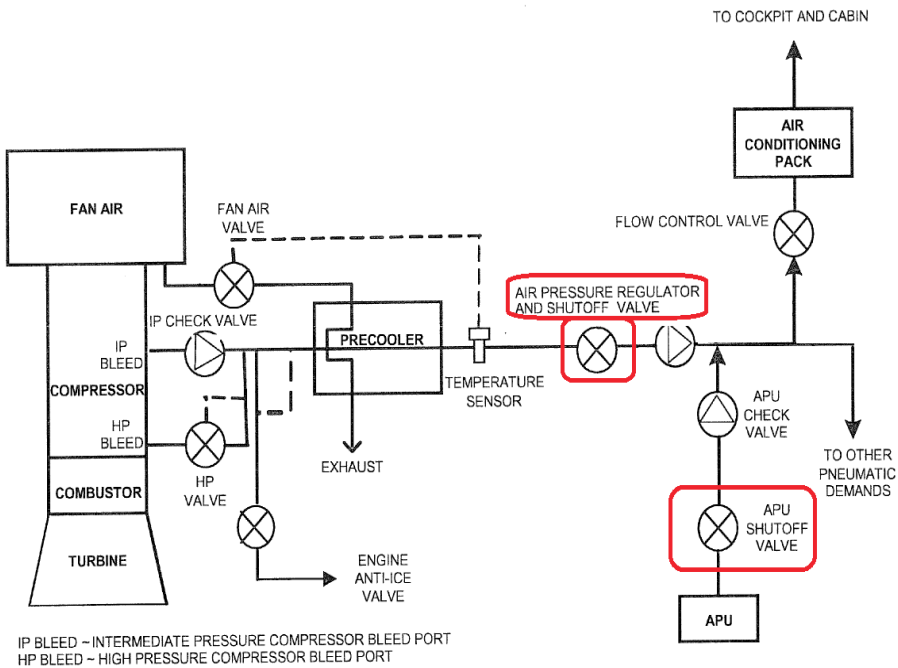


Figure 9. Bleed Air Shut-off Valve (SAE Standard, 2020)

The shut-off mechanisms should be controlled by the crew in cockpit. Inspection of SDD and drawings verify that shut-off means are designed in a safe manner.

Criteria for safe manner may be the optimum distance of shut-off means from the source. JSSG expresses that the most appropriate location for these provisions is near the bleed port of the engine (DoD Standard, 2013).

Safety analysis provides that failure of the bleed air system is within the allowable limits. It is recommended to analyze the failure of the bleed air shut-off function in the safety analysis.

The operation of bleed air shut-off provisions is verified for the normal operating condition in ground and flight tests.

The means of compliance with the requirement are MC1, MC3, MC5, and MC6.

### 2.13 Pressurization Stabilization Control

Criterion as it has been stated in the standard: “Verify that pressurization rate control is available to preclude pressure surges in the cockpit, control station, and avionics environment” (DoD Standard, 2014).

Military combat aircraft usually employ a fixed isobaric and differential pressure schedule as illustrated in Figure 10 (SAE Standard, 2015).

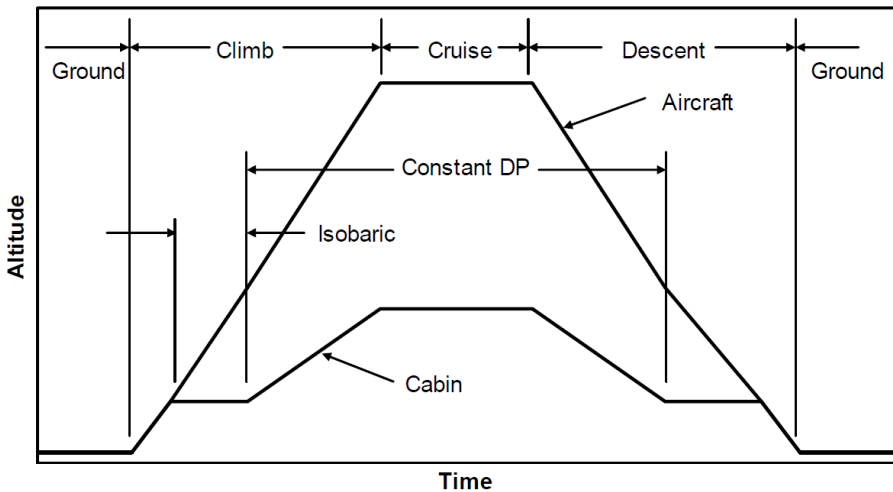


Figure 10. Typical Cockpit Pressure Schedule for Military Aircraft (SAE Standard, 2015)

The inspection of SDD provides the designed pressure schedule for the fighter aircraft. It is recommended to reconsider the pressure schedule when collective NBC protection (DoD Standard, 2013) is operating in the aircraft.

Safety analysis provides qualitative and quantitative data about the failure condi-



tions of the pressurization system including the safety critical components. Since the system is safety-critical, a safety design approach such as redundancy and independency should be considered and given as mitigation in the safety analysis.

Analysis and flight tests verify that the system can adapt to the changes in the altitude. This can be accomplished only by an automatic system with a fast response. The commonly accepted tolerance is 0.2 psi for the pressurized range and 0.5 psi for the unpressurized range (SAE Standard, 2011). Laboratory test may not give the exact results about the dynamic response, interaction of the engine bleed system, pressurization system, and flight conditions. Flight tests are required for steady-state and transient conditions. The ground test is conducted to demonstrate the relief ways (DoD Standard, 2014).

The pressurization system components, such as the outflow valve, safety relief valve, and control elements, should be tested in laboratory to confirm that they are operational throughout the envelope.

The means of compliance with the requirement are MC1, MC2, MC3, MC5, MC6, and MC9.

### 2.14 Nuclear, Biological, and Chemical (NBC) Protection Provisions

Criterion as it has been stated in the standard: “Verify that NBC equipment and/or procedures are provided for protecting or maintaining environmental control system air free from contaminants” (DoD Standard, 2014).

Nuclear, biological, and chemical materials penetrate the aircraft via the bleed air or ECS inlet/vents. Three ways to protect aircraft against NBC attack are individual protection, collective protection, and a combination of these two (SAE Standard, 2011) as illustrated in Figure 11.

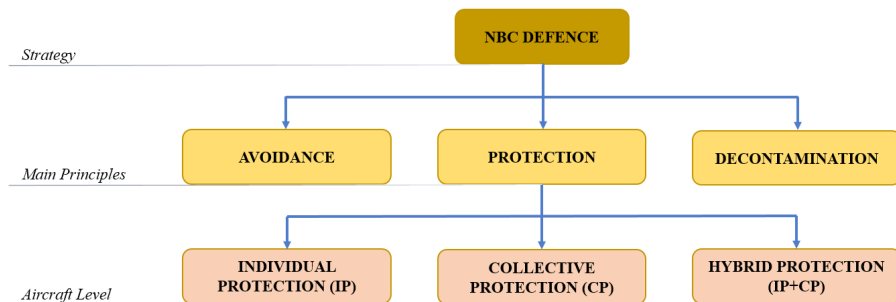


Figure 11. Strategy for NBC Defence (Based on author’s knowledge)

Individual protection requires the protection equipment which is involving a res-

piratory system and a protective suit. On the other hand, the collective protection means that the overpressure system which is the built-up of purified air in the aircraft as illustrated in Figure 12.

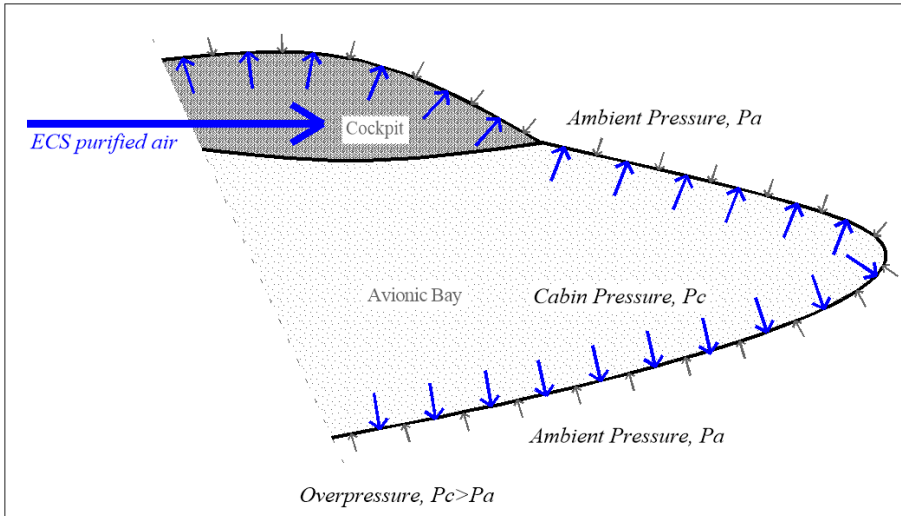


Figure 12. Schematic of Overpressure in Aircraft (Based on author's knowledge)

SDD can give technical explanations about the protection methods as a compliance document. Training curriculum, flight and maintenance manuals supply the procedures for flight safety under all operating conditions.

Showing compliance with the requirement may be exhaustive since live agent testing can only show that NBC operates as designed (DoD Standard, 2013). A chemical simulant may also be an option for laboratory tests. A flight test is always the final verification method to analyze the requirements. However, it may not be the proper case since an appropriate environment may not be provided on the flight.

NBC protection may not be considered an airworthiness requirement with the consensus between the applicant and the military authority. However, it should be checked that any hardware or software of NBC protection should not cause ECS to reduce its reliability in all flight conditions, whether it is operational or not.

The means of compliance with the requirement are MC1 and MC4.

## 2.15 Thermal Management

Criterion as it has been stated in the standard: "Verify that the air vehicle's ther-

mal management system is stable and meets all safety of flight performance requirements throughout the design envelope” (DoD Standard, 2014).

Thermal design is presented in SDD, such as components, control elements, operating sequence, interface with heat-released equipment, and other technical details. Inspection of SDD provides safety precautions and performance parameters such as operating procedures of thermal management in an emergency.

Thermal analysis or cockpit thermal balance analysis shows that ECS provides a suitable environment not only to pilot but also to safety-critical avionics, including the data such as the required mass flow rate and supply temperature as defined in the Equation (1).

$$Q_{in} - Q_{out} = \Delta Q_{storage} = m_{supply} \times c_p \times (T_{supply} - T_{cockpit}) \quad (1)$$

where:

- $Q_{in}$  : Heat gain by the cockpit interior, (in kW).
- $Q_{out}$  : Heat loss from the cockpit interior to the ambient, (in kW).
- $\Delta Q_{storage}$  : Change in heat within the cockpit, (in kW).
- $m_{supply}$  : Required mass flow rate to keep the temperature inside the cockpit same, (in kg/s).
- $c_p$  : Specific heat for the supplied air, (in kJ/kg.K).
- $T_{supply}$  : Supply air’s temperature, (in K).
- $T_{cockpit}$  : Cockpit interior air temperature, (in K).

The components for heat gain by the cockpit interior ( $Q_{in}$ ) are expanded in Equation (2).

$$Q_{in} = Q_p + Q_s + Q_c + Q_A + Q_L + Q_V \quad (2)$$

where:

- $Q_p$  : Sensible heat gain due to the pilot’s metabolism, (in kW).
- $Q_s$  : Heat gain due to the solar radiation, (in kW).
- $Q_c$  : Heat gain from the adjacent compartments, (in kW).
- $Q_A$  : Heat gain due to the heat releases from avionics, (in kW).
- $Q_L$  : Heat gain due to the heat releases from cockpit lighting, (in kW).
- $Q_V$  : Heat gain due to the aerodynamic heating, (in kW).

The components for heat loss from the cockpit interior ( $Q_{out}$ ) are expanded in Equation (3).

$$Q_{out} = Q_{cond} + Q_{conv} + Q_{rad} + Q_{evap} \quad (3)$$

where:

- $Q_{cond}$  : Heat loss due to the conduction through the cockpit surfaces, (in kW).
- $Q_{conv}$  : Heat loss due to the convection by the air flowing over the cockpit surfaces, (in kW).
- $Q_{rad}$  : Heat loss due to the radiation from the cockpit surfaces, (in kW).
- $Q_{evap}$  : Heat loss due to evaporation of sweat from the pilot, (in kW).

In the aspect of thermal management in the cockpit, pilot envelope temperature is a satisfactory requirement for military aircraft, and it should be included in the thermal analysis. Pilot envelope temperature gives the measurement at the ankle, knees, hips, chest, shoulders, and head (DoD Standard, 2014).

SSA provides that there is no loss of critical function in the case of ECS's failure.

A test rig helps to identify problems early before proceeding to ground and flight tests.

Components in the system should have the required qualifications regarding their installation zones and conditions that they are exposed to. Equipment qualification documents should be submitted to verify the requirement.

Final verification is provided with ground and flight tests. Flight tests in the only method to confirm the performance under all operating conditions.

The means of compliance with the requirement are MC1, MC2, MC3, MC4, MC5, MC6, and MC9.

## 2.16 Smoke Removal

Criterion as it has been stated in the standard: "Verify adequate smoke clearance is available to ensure safe operation with or without an operational ECS" (DoD Standard, 2014).

Smoke may be originated from onboard sources apart from the bleed air source. There are many onboard smoke or fume sources, such as electrical components, fans, fuel, exhaust, hydraulic fluids, duct insulation, deicing fluid, and air conditioning packs (Anderson, 2021). In the condition of smoke or fume in the cockpit, the smoke removal system is designed to provide a safe environment over the flight envelope.

Inspecting drawings shows the provisions for emergency ventilation and smoke removal. However, the performance which is the time to remove the smoke

from the cockpit, is required to be evaluated with analysis and verified by tests.

Safety analysis provides the failure condition, such as loss of ventilation in case of smoke (both main and emergency ventilation), to verify that failure classifications and probabilities are within the design limits to sustain the flight safety.

The means of compliance with the requirement are MC1, MC2, MC3, MC5, and MC6.

### 2.17 Surface Touch Temperatures

Criterion as it has been stated in the standard: “Verify that all surface touch temperatures remain within required limits to maintain the safety of flight operations of the air vehicle” (DoD Standard, 2014).

All surfaces that the crew can touch should be maintained within the allowable limits to preclude thermal contact hazards (DoD Standard, 2013). Temperature exposure limits are illustrated in Table 5. Surface temperatures should be checked to show compliance with the requirement.

Table 5. Temperature Exposure Limits (DoD Standard, 2012)

Exposure	Temperature Limits		
	Metal	Gas	Plastic or Wood
Momentary contact	60°C	68°C	85°C
Prolonged contact or handling	49°C	59°C	69°C

Analysis, component tests, and ground/flight tests verify that surface temperatures are within the safe limits for human (DoD Standard, 2014).

Safety analysis should be performed to ensure no hazards are observed and that is verified in the flight test.

The means of compliance with the requirement are MC2, MC3, MC5, MC6, and MC9.

### 3. Recommendations For Compliance Strategy

The recommended technical descriptions for compliance strategy not included in MIL-HDBK-516C are listed below:

- MIL-HDBK-516C recommends conducting a ground test for alternate cooling. However, the ground test may not be an appropriate method to analyze

safe return or mission completion concepts. They should be verified in the flight test.

- Laboratory tests prior to the flight test may help to show that interaction between regulators are as expected for pressurization.
- It is recommended to check data about conditioned maintenance in AMM to preclude any unexpected failure of components that are highly sensitive to contaminated environments.
- It is crucial to specify the critical view area for safe operation in environmental protection. The critical view area should always be kept clear throughout the flight envelope. Moreover, it is recommended that temperature limit control in the hot air supply line for defog should be verified for compliance with the requirement considering the failure case in ECS. Freezing rain may cause safety problems at ECS's vents even if ice formation is tolerable and no ice protection is designed.
- The document, including bleed air gas concentration data from the engine manufacturer, should be submitted to show that substances are below the maximum allowable concentration for flight safety to verify the requirements for air quality.
- The leak detector sensors should be tested in laboratory to make sure that they can operate in the desired environment and recover after disclosure to the leakage.
- It is recommended to install the shut-off provisions near the bleed port of the engine to stop the bleed airflow when required.
- It is recommended to reconsider the pressure schedule when collective NBC protection is operating in the aircraft. CPCS should act quickly to adapt to changes in flight altitude. This can be accomplished only by a quick-reacting, automatic system with a usually 0.2 psi for the pressurized range and 0.5 psi for the unpressurized range.
- NBC protection may not be considered as airworthiness requirement with the consensus between the applicant and the military authority. However, it should be checked that any hardware or software of NBC protection should not cause ECS to reduce its reliability in all flight conditions, whether it is operational or not.
- Pilot envelope temperature is a satisfactory requirement for military aircraft and should be included in the thermal analysis. Pilot envelope temperature should include measurements of ankle, knees, hips, chest, shoulders, and head.
- Smoke removal time should be evaluated by analysis and verified by tests. 4.

#### 4. Conclusion

A compliance strategy, including a systematic approach with the coordination of other interlinked systems, is necessary to assure safety in military applications since the certification activities have high complexity and many interfaces, and there is no common rule for verification methods.

Academic education, such as recommended practices from many standards and technical information from the handbook, is reviewed. Besides, vocational training, such as experience in the field, is mixed with academic education to prepare a comprehensive compliance strategy for airworthiness certification of ECS in military applications presented in this study.

In the aspect of the certification, the compliance strategy provides the followings:

- Specific safety requirements to ECS for the safety of flight.
- The coordination with other systems responsible that has an interface to get the maximum technical support to verify the requirements.
- Certain means of compliance with a comprehensive technical explanation to show compliance with the requirements.
- Specific technical information must be observed, measured, or searched in the documents or tests since it is crucial to the system's safety.

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#### Conflict of Interest

The author declares no known conflict of interest.

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