International Journal of Innovative Research in Computer Science and Technology (IJIRCST)
ISSN (Online): 2347-5552, Volume-13, Issue-3, May 2025
https:/doi.org/10.55524/ijircst.2025.13.3.23
Article ID IJIRE-1403, Pages 149-161
www.ijircst.org

Investigation of Black Soot-Induced Degradation of Environmental Control Systems (ECS) & Aircraft Avionics Failures

Haroon Saqlain Khan[1], Dr. Ayusha Abbas[2], and Aftab Ali[3]

[1] Graduate Researcher, School of Chemical and Mechanical Engineering (SCME), National University of Science and Technology (NUST), Pakistan
[2] Research Scientist, Department of Electrical & Electronics Engineering, Newcastle University, UK
[3]Aerospace Maintenance Engineer, Abu Dhabi, United Arab Emirates (UAE)

Correspondence should be addressed to Ayusha Abbas ayusha.abbas@ymail.com

Received 19 April 2025; Revised 3 May 2025; Accepted 18 May 2025

ABSTRACT- Efficient and effective cooling of aircraft avionics is required to achieve optimized performance, reliable & extended operation. Thus, rated temperature ranges for safe operation of avionics are ensured by employing Environmental Control System (ECS) in aircraft, which uses ram air in closed circuits to cool avionics Line Replaceable Units (LRUs). Heat is dissipated out into the closed-circuit ram air stream (sink) from the PCB cards (source) via forced convective heat exchange. During this process, heated components leave soot particles into the downstream which are subsequently condensed & accumulated in the ECS components (in the form of black soot). Being a good insulator of heat, it reduces efficiency of ECS system over the years by decreasing heat transfer rate. Whereas, inspections of ECS components (permanently closed hollow walls of avionics LRUs) are not a part of Scheduled Preventive Maintenance Programs (SPMPs) at field level in aviation industry. Therefore, the soot deposition goes unchecked until the LRUs are replaced as “condition-based item” which resultantly may cause degradation of performance of aircraft avionics, burning of PCBs due to overheating due to reduced efficiency of ECS because of black soot deposition phenomena. This research has investigated degradation of ECS system performance due to ageing & black carbon soot using empirical, experimental & CFD methods. It was found that black carbon soot deposition in ECS contributes 11% rise in operating temperature of avionics LRUs.

KEYWORDS- ANSYS, Environmental Control System (ECS), Cooling of Avionics, Heat Exchangers, Fluent.

I. INTRODUCTION

Aviation industry is indeed one of the most admirable industries of today’s world. It has not only enabled humans to fulfill the dream to fly but also ensured that every human flight is safe and reliable. However, 100% flight safety can only be ensured if every aircraft is equipped with well-integrated flight systems of very high reliability. All aircraft systems are dependent upon multiple avionics units for their operation. These avionics units form an essential part of the aircraft flight systems. On average a commercial aircraft may have 80 to 150 different LRUs of all avionics systems and a fighter aircraft may have 60 to 170 LRUs of all avionics which may vary as per role and task of the aircraft for which it is designed and subsequently equipped. Primary function of ECS system is to regulate temperature of cockpit, passenger cabin & avionics bays. ECS systems are operating on forced convective cooling principle which can either be closed or open circuit. Closed circuit cooling operation involves a cooling media such as air, water or other liquid flowing inside the tubes/ closed ducts of the heat exchangers & act as a sink whereas the hot air incoming from the avionics is passed over these ducts to exchange the heat. The overall size of the heat exchanger and used cooling agent (liquid or air) in a forced convective cooling ECS depends upon the electronics output / heat dissipation rate. More high-power electronics installed in a bay more difficult it is to design an efficient thermal management system or cooling system. ECS system regulates this heat by manipulating the variables like mass flow rate of air inside the forced cooling ducts, specific heat capacity of the cooling agent used, surface area of the heat exchanger (source over sink area), material properties of the heat exchanger duct such as porosity, co-efficient of thermal heat transfer etc. Visual representation of housing of different avionics & routing of the ECS ducting in aircraft is given below in Figure 1.

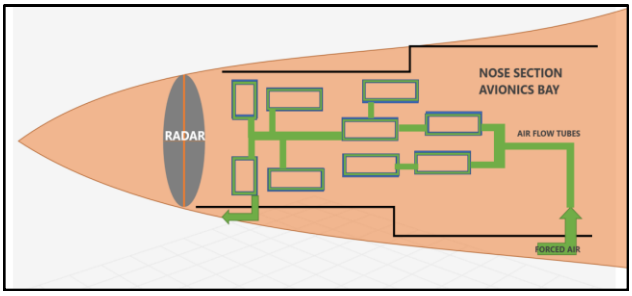

Figure 1: Schematic of Nose Section of an Aircraft showing ducting of ECS system through Avionics LRUs

A. Process of Heat Flow from Avionics LRU to Ambient Air

Before proceeding into investigations of how inefficiencies take place in the cooling system due to environmental factors like deposition of black carbon soot & corrosion it is important to understand the details of how heat transfer takes place from LRU into the avionics ducts and what are the variable & their empirical relations with each other. Consider Figure 2 given below, it illustrates flow direction of heat from the PCBs installed inside the housings of LRU into the cooled air circulated within the walls of the LRU housing. It is important to highlight that LRU housing have hollow walls which are ducted to accommodate the circulation of forced air through them. The circulated air is moving in between two walls of the housings of LRU as indicated by blue arrows & heat flow direction indicated by green arrows.

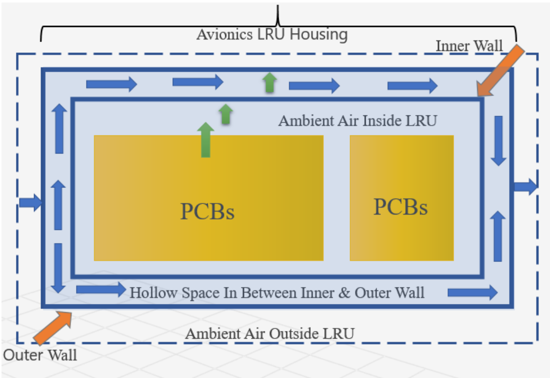

Figure 2: Heat Transfer Modelling of ECS - Forced Convective Heat Transfer

Complete heat transfer can be sub-divided into following stages:

Heat Flow	Interface Boundries	Heat Transfer Method
Stage 1	PCBs	Convective Heat Transfer
Stage 2	PCBs to Air Inside LRU Housing	Convective Heat Transfer
Stage 3	Heat Flow Within the Air Inside LRU Housing	Convective Heat Transfer
Stage 4	Air Inside LRU Housing to Inner Surface of Inner Wall of LRU Housing	Convective Heat Transfer
Stage 5	Inner Surface of Inner wall to Outer Surface of Inner Wall of LRU Housing	Conductive Heat Transfer
Stage 5	Outer Surface of Inner Wall Into Forced Cooling Ram Air	Forced Convective Heat Transfer
Stage 6	Forced Cooled Ram Air to Inner Surface of Outer Wall of LRU Housing	Forced Convective Heat Transfer
Stage 7	Inner Surface of Outer Wall to Outer Surface of Outer Wall of LRU Housing	Conductive Heat Transfer
Stage 8	Outer Surface of Outer Wall into Ambient Air	Convective Heat Transfer

B. Effect of ECS on Engine Performance of an Aircraft

Since we understand that ECS uses regulated & controlled ram air to cool the LRUs of avionics. This ram air is bled out from the engine compressor stage & feed to the heat exchangers for regulation of temperature & mass flow rate. The temperature & mass flow rate of the circulated air are two important variables which have following relationship with the effectiveness of the ECS.

- Lower the temperature in the circulated air in ECS higher will be the heat transferred from the avionics LRUs & thus better will be the efficiency.
- Higher the mass flow rate (kg/sec) of the circulated air higher will be the heat transferred from the avionics LRUs & thus better will be the efficiency.

Both of these variables are optimized to regulate the circulated air in such a way that PCBs/ electronic circuits inside the LRU housings of avionic systems keep on operating at normal temperature ranges (25 – 40 Degree Celsius). However, the factor of safety in designing ECS system doesn't offer higher margins because there are limitations to which air can be drawn from the engine compressor because more the air bleed out of the compressor the more decrease in engine performance will have to be faced.

C. Effects of Degraded Performance of ECS on Aircraft Avionics Systems

Avionics systems have very sensitive electronic circuits / PCBs installed in them. These circuits include semi – conductors and plastic components which are designed to perform in normal operating temperatures. But at the meantime these circuits dissipate very high heat as they are operating on high power outputs (in order of KW). If in case temperature at the electronic circuits remains elevated due to degraded performance of ECS/ avionics cooling system it may affect avionics performance in different domains. For example, the semi – conductor chips installed in the avionics will lose their performance due to high activation energies, the organic substrate of PCB cards may melt / burn off, the metal parts will bear excessive thermal stresses & electrical connectors / antennas will lose their circuit constants. It is proven in previous studies that if avionics are operated at elevated temperature during routine flying it will increase the failure rate of avionics which subsequently will have financial & operational bearing. Whereas, degraded performance of aircraft ECS has been reported to be one of the primary factors behind the unscheduled maintenance by the aircraft operators [1]. Moreover, reliability of avionics is inversely proportional to temperature range in which avionics are operating. Failure rate of avionics increases if they are operated in high temperature ranges [2].

D. Thermal Failures of Avionics Due to Black Carbon Soot in ECS

Since, the black carbon soot is an insulator of heat being organic in nature it decreases the heat transfer rate across the LRU walls from heat source (PCBs) into the sink (ambient air). The phenomena of black carbon soot deposition inside the avionics LRUs were identified & validated during MRO of a fourth-generation fighter aircraft by the author. Similar phenomena such as reduced performance of electronics due to deposition of dirt/ dust & smoke was reported by different authors previously in literature. A detailed study has been carried out [3] to explore the possible ways in which black carbon soot/ smoke will affect the performance of electronics which explains that if electronics are exposed to black carbon particles the performance of electronics will be affected in three possible ways:-

- Indirect effect of black soot is the rise in ambient temperature beyond critical temperatures which causes the semiconductor components to fail (thermal malfunction).
- Direct effect of black soot/ carbon particles on the electronics in which the electrical component fails because of current leakages & short circuiting induced due to black carbon particles due to formation of conductive carbon bridges.
- Another direct effect of black carbon is the decreased thermal inertia of electronic components due to high thermal diffusivity of the soot deposition.

E. Modelling of ECS for CFD

As explained earlier, if heat transfer from inside the LRU housing into the circulated ram air is not carried out efficiently the temperature at the PCBs inside the LRUs will rise which will result into avionics thermal failure or decreased avionics performance & reliability. The heat transfer efficiency of ECS will decrease if black soot and other contaminations are deposited inside the closed ducting of ECS/ avionics LRUs because it will act as an insulating layer. However, in order to carry out CFD and investigate the fact that deposition of black soot inside LRUs / ECS ducts will actually raise temperature at PCBs to a limit sufficient to cause a thermal failure requires accurate CAD modelling, accurate air flow modelling through the ECS & accurate heat transfer model incorporating each stage of heat transfer and corresponding heat transfer mode (conductive, convective or forced convective).

II. LITERATURE REVIEW

Air flow modelling inside the ECS ducting requires accurate modelling of turbulence properties at the corners of the LRUs & it should also incorporate the friction effects, heat dissipation or temperature profile effects and forced momentum of the flow due to inherent ram air velocity and most importantly the effects of black soot and contaminations on the flow & heat transfer. In this regard boundary layer conditions and separations at the corners becomes a prominent problem from modelling perspective. Air flow separation of ram air in ECS LRUs can induce inefficiency in heat transfer rate however it can be overcome if passive flow control method is used in LRUs/ ECS ducting. One of the most practically viable and experimentally validated passive flow control techniques identified in recent literature is the Optimum Trapped Vortex Cavity (OTVC), which was effectively implemented in a recent study [4] to achieve robust and reliable airflow control—demonstrating significant aerodynamic performance improvements while maintaining computational efficiency. Power performance of 2-D H-type VAWT was increased by using an optimum cavity on NACA 0018 blade airfoil. Computational cost was reduced using the GPR (Gaussian Process Regression) model coupled with the Genetic Algorithm at static stall angle of attack in an isolated environment. 80 CFD simulations were run to reduce computational efficiency by 97% and it was confirmed in the results that aerodynamic efficiency of optimum cavity has only 0.5% difference with the predictions of GPR. In near stall regions 31.8% aerodynamic efficiency was improved due to utilization of optimum cavity on the VAWT aerofoil in comparison to the clean surface. It depicts that such passive flow control methods being very cost effective and practically viable can also be used in ECS to make heat transfer more efficient. However, since in the ECS the mass flow rate entering the avionics LRUs is a critical control variable to determine the final temperature maintained at the PCBs thus the advantages gained in terms of reduced flow separations will have to be optimized for the de-merits like increased complexity, careful maintenance. But utilization of this concept for ECS is still novel and careful CFD analysis can be carried out to cater for the flow optimization in the ECS.

Artificial Intelligence is a fruitful tool which has enabled modern world technologies. AI has been used for the flow optimization problems & heat transfer problems in literature in conjunction with the conventional CFDs. AI based machine learning (ML) algorithms can be used to increase the design aspects and profiles of various aerodynamic structures. ECS ducting and LRUs can be configured for optimized layout, positioning & housing/ chassis design using ML algorithms under given control variables such as mass flow rate & heat dissipation from the LRUs. In a recent study [5] ML was used in conjunction with the CFD to improve the design and functionality of wind turbine blades & optimization of geometry & shapes of wind turbine blades was carried out to achieve the flow optimization. Aerodynamic drag and turbulence were minimized without compromising the energy output. An important edge of ML lies in its capacity to leverage the vast datasets and advanced simulation tools to bridge the gap between theoretical models and practical utilization. However, since ML requires a baseline data set to process the optimization it's a limitation for improvement of ECS from design perspective as no such structural datasets will be readily available for some conclusive analysis.

Another leading and widely adopted passive flow control strategy to increase the flow optimization is use of bio inspired leading edge tubercles systematized in [6]; this can be a novel approach if used in ECS as tubercles can be used in the corners of ducting to enhance the flow of ram air inside the ducts ensuring optimized heat transfer rate. Low power coefficient of VAWTs is a limitation which was enhanced by employment of tubercles by using hybrid design of Experiments (DoE) approach & Response Surface Methodology (RSM) instead of random values of tubercle variables & CFD was run on unsteady conditions using a four-equation transition SST turbulence model. At off design conditions maximum of 55 % performance was enhanced for the VAWT.

Computational cost of CFD is one of the major limiting factors in modelling of a complete aircraft ECS system because it involves more than 170 LRUs as explained in introduction part. However, in recent studies [7] & [8], a robust framework that integrates a Potential Flow Solver (PFS) with geometry parameterization techniques has been developed allowing high-fidelity aerodynamic analysis while achieving approximately a threefold reduction in computational cost compared to conventional CFD approaches. Such a framework holds significant promise for modeling the complete aircraft Environmental Control System (ECS), offering both high accuracy and computational efficiency.

CFD results require both experimental and numerical validation to ensure credibility and acceptance. The Environmental Control System (ECS) of an aircraft can be physically tested in a wind tunnel by fabricating a scaled-down model using advanced additive manufacturing techniques. A practical methodology presented in the study [9] allowing testing and manufacturing of models with high precision and reducing fabrication lead-time significantly can be adopted to for the development and testing of high-precision ECS models in more accurate, efficient and cost-effective way.

CFD is essential for analysis of inefficiencies of airflows & heat transfer across the ECS & avionics LRUs however turbulence modelling is expensive & time taking high fidelity CFD. In a recent study, AI based turbulence modelling framework introduced by [10] proposed integration of Physics-Informed Neural Networks (PINNs) with traditional CFD solvers to accelerate high-fidelity simulations. Resultantly, AI-augmented CFD simulations were found to be 70% faster. Thus, cost & time have been reduced significantly whereas accuracy is maintained meanwhile. AI based model has also captured complex flow structures & interactions effectively as compared to conventional CFDs.

In a similar study [11], more practical and advanced AI - based technique was pioneered allowing shape & flow optimization using a Generative AI-driven aerodynamic shape optimization framework which leverages deep neural networks to streamline the optimization process. Generative adversarial networks (GANs) and variational auto encoders (VAEs) were used to generate and refine aerodynamic shapes with optimal performance metrics. Physics informed ML was incorporated and benchmark case studies including airfoil and automotive body designs were optimized using this AI driven shape optimization model. Superior efficiency was recorded in comparative analysis again adjoint-based solvers. Thus, for better modelling of ECS physics-based ML can be used as a practical tool.

Ensuring manufacturing accuracy and geometric fidelity is critical for achieving optimal airflow performance in the ECS. Inaccuracies in translating CAD designs into physical prototypes can introduce performance deviations that undermine the validity of simulation-based predictions. To address this, in a recent study [12] more practical and validated experimental framework was introduced that integrates reverse engineering with high-fidelity deviation analysis. By employing point cloud data and surface deviation metrics—captured via laser scanning and Coordinate Measuring Machines (CMM)—this approach quantitatively assesses the discrepancies between manufactured components and their original CAD models. Such a methodology is instrumental in enabling the precise fabrication of aerodynamically optimized ECS configurations.

For better design of ECS / optimized cooling of each avionics LRU in the overall setting/layout of ECS is critical. The choice of a geometry parameterization technique plays a critical role in achieving an optimized system by enabling effective design space exploration with a reduced number of variables, as demonstrated in a recent study by [13]. The study also introduced a comparative performance metric, providing a systematic basis for selecting the most suitable parameterization method by evaluating their relative efficiency and effectiveness. Based on the recent findings, the Free Form Deformation (FFD) parameterization can be used in this study allowing ECS system optimization effectively.

III. RESEARCH METHODOLOGY

In order to investigate temperature, rise at PCBs due to reduced heat transfer rate in ECS because of inherent inefficiencies due to air flow disturbances and disposition of black soot and other environmental contaminations inside the ducting of ECS we can follow three approaches as following:-

- Empirical Calculations & Case Studies
- CFD Analysis of ECS
- Experimental Findings

A. Empirical Calculations & Case Studies

30 avionics LRUs of a fourth-generation fighter aircraft were examined at an I level maintenance facility in order to record the observations regarding black carbon soot deposition inside the ECS system. Calculations for temperature rise at PCBs were carried out using empirical relations available in literature in order to make a set of

data which can be compared for validation of results obtained from ANSYS simulations and own experimentations. Out of all avionics two different LRUs named SAIU & WMMC were studied in details because multiple occurrences of overheating and damages associated to overheating were found in these two LRUs of different aircraft at different occasions. Calculations revealed that those LRUs in which black soot were found had stayed overheated for longer durations and thus signs of burning of PCBs and deformation/ buckling of housing walls were registered in those LRUs. Detailed account of these investigations carried out at field level are discussed separately.

B. Black Carbon Soot Depositions in Standard Armament Interface Unit (SAIU) – A Case Study

SAIU is an LRU of a fourth-generation fighter aircraft. PCB cards of SAIUs of different aircraft were reported to be burnt. Figure 3 shows burnt PCB card (left) and deposits of black soot at the back side of LRU (right).

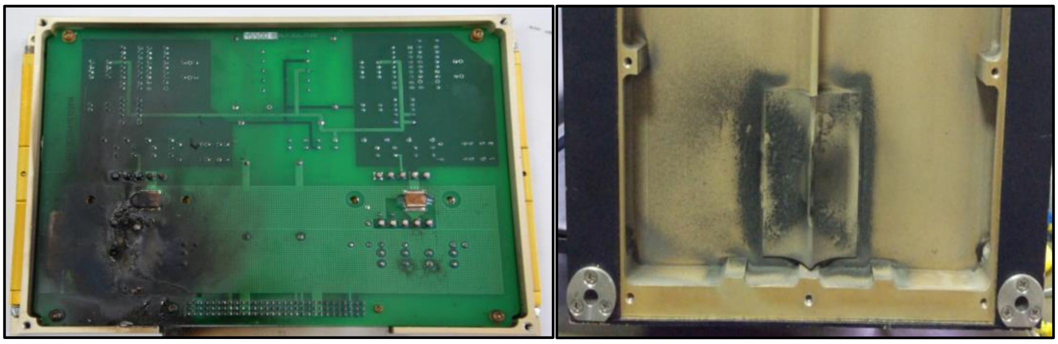

Figure 3: Burnt PCB Card of SAIU(left). Black Soot depositions in ECS ducting of LRU (Right)

Litovisky & Shappiro [8] has studied in detail that how much a black soot layer will decrease the thermal heat transfer co-efficient of any metal surface. In equation of conductive heat transfer for a metal plate (given below) if we examine reduction of k for constant value of Q, L, A & T cold will eventually increase the T hot.

$$Q = \frac{k \; x \; A \; x \; (T \; hot - T \; cold)}{L}$$

It can be re-written as

$$Thot = \frac{L \; x \; Q}{A \; x \; k} + Tcold$$

Whereas,
Q = Heat transferred
k = coefficient of conductive heat transfer
A = Surface Area of the Wall
T hot = Temperature at the inner surface of the housing wall (Heat Source Side)
T cold = Temperature at outer surface of the housing wall (Heat Sink Side)
L= Thickness of LRU housing wall
Effective value of k after black carbon soot deposition on the surface of a metal plate can be governed by following equation:-

$$Ksoot = Ks \; [1 - n)1.5 + n0.25 \; (Kp/Ks)$$

Where,
K soot= Thermal Conductivity Coefficient of black carbon soot
Ks = Thermal conductivity coefficient of metal (in our case it is aluminum= 205 W/mK
"n" = porosity of the metal (we will consider Aluminum 2000 series with porosity n= 0.45)
Kp = Diffusivity of carbon particles / thermal conductivity co-efficient of carbon powder which as per Pedraza and Kelmen can be considered as 37.4 W/m.K.

So, if above equation is solved for K soot, we get 173 W/mk. If this value is plugged for Q T hot will be increased from 65 deg C to 73 deg C (10% increase) for Q = 15Kw = rated power of SAIU.
However, this porosity value n = 0.45 is for healthy aluminum. In our case the SAIU LRU will have even more value of n because of ageing/ corrosion because corrosion increases the value of porosity [10]. Therefore, for values of n = 0.55 we get value of Ksoot = 143 W/m K and the T hot = 83 Deg C.
We can conclude that PCB will be operating at temperature 83 Deg C instead of 65 Deg C if black carbon soot depositions are present in SAIU LRU. ECS will be now have to reduce temperature to 40 Deg C from 83 Deg C instead of 65 Deg C. So effectively, ECS will show degraded performance and final temperature at the PCB after incorporation of ECS cooling effect will be around 65 Deg C. Whereas, a PCB will fail thermally within 300 seconds at 90 Deg C. So, if SAIU PCBs were subjected to prolong operations at 65 Deg C eventually, circuit disruptions due to elevated temperatures lead to short circuiting & subsequent burning of the PCBs in SAIU LRU.

C. Structural Failure of Weapon Mission Management Computer (WMMC) Housing due to Overheating Caused by Black Carbon Soot Depositions – A Case Study

Overheating due to inefficiencies of ECS has caused not only the burning of PCBs due to overheating but it can also cause mechanical/ structural failures / deformations of LRU housings. As a case study it was empirically calculated for WMMC LRU that buckling of side panel of WMMC is because of overheating of LRU. An LRU of WMMC with buckled wall highlighted in red circle is shown in Figure 4.

Figure 4: Buckling of Wall in LRU of WMMC

Thermal elongations & stresses caused due to thermal elongation and following relation was found for uni-directional elongations:-

Stress = Modulus of Elasticity of Material × Strain

Whereas Strain = ▲L/ L

Where, ▲L= elongation of panel, L = original length of the panel

Whereas, the ▲L due to temperature rise can be calculated using relation

▲L= L (α) ▲T

Where, α= co-efficient of linear thermal expansion, ▲T= Temperature Rise

So, to proceed further with the calculations of stress due to elongation it is pertinent to mention that ECS passage through the housing of WMMC was inspected to trace the black carbon soot depositions and its presence was confirmed. Figure 5 shows the black marks of overheating and deposits of black soot:-

Figure 5: Housing of WMMC LRU with Black Soot

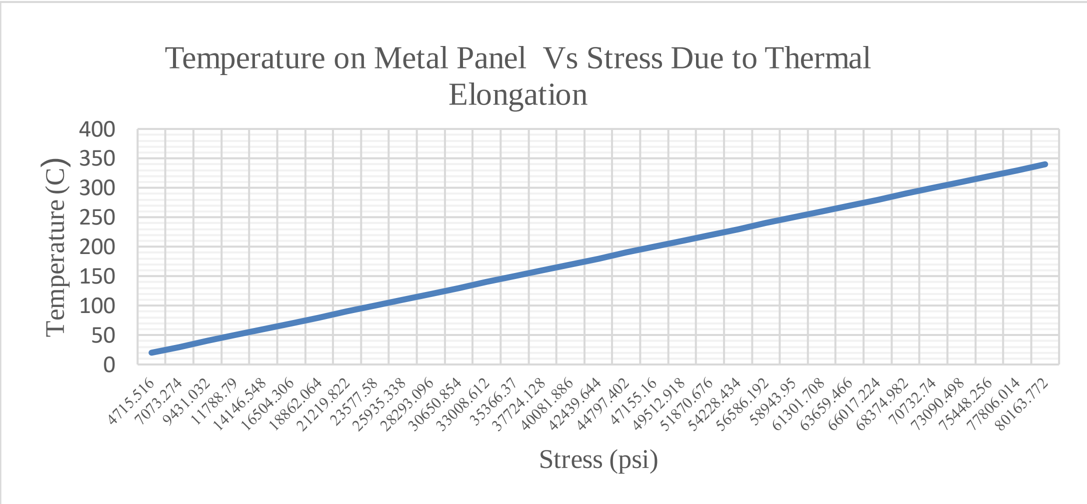

Figure 6: Stress Due to Thermal Elongation vs Temperature Rise at LRU Housing Due to Black Carbon Soot

It can be deduced from the graph presented in Figure 6 above that by using empirical relations already discussed, increase of temperature by 30 Degree C shall generate a stress of 7073 psi which is 17% of the tensile strength of aluminum and sufficient to create a bend in buckling. As per Euler's buckling equation buckling stress can be calculated as follows

$$\sigma = \frac{F}{A} = \pi^2 \, x \, \frac{EI}{L^2}$$

Wall of WMMC LRU bucked has dimensions as length 340 mm & 190 mm width however the Euler's buckling equation for pinned – pinned type joint was solved for 50 mm x 190 mm dimensions (buckled piece between two fasteners). 5,529 psi came out to be the stress required to buckle the wall whereas stress caused due to thermal elongation is 7073 psi. Hence, it was proved that black carbon depositions caused structural failures of avionics LRU housings such as "buckling of side wall".

D. CFD Analysis of ECS

Available modules of ANSYS were compared for most accurate modelling of heat transfer problem of ECS and following comparison was drawn:-

Table 1: Selection of Suitable Module of ANSYS

Problems / Modelling	FLUENT			ICEPAK
	General Solver Settings	Heat Transfer	Solid Structure Interaction	Electronic Cooling
CAD Model of Complete ECS Including Connections of Multiple LRUs	✓	✓	X	X
Variation of Mass Flow Rate Of Forced Ram Air	✓	✓	✓	✓
Variation of Temperature Of Forced Ram Air	✓	✓	✓	✓
Constant Heat Source At PCBs	✓	✓	✓	✓
Fluid Properties of Forced Ram Air	✓	✓	✓	✓
Heat Transfer Between LRU Walls And Forced Ram Air	✓	✓	✓	✓
Heat Transfer Through The Forced Cool Air	✓	✓	✓	X
Material Properties Of LRU Housing Walls	✓	✓	✓	✓
Modelling Black Carbon Soot & its effects for complete ECS Ducts and Net Temperature Rise at PCBs	✓	✓	X	X
Temperature Rise at PCBs of Single LRU	✓	✓	✓	✓

A single LRU places in ECS system was modelled and studied under normal conditions at first step. CAD modelling was carried out to cater for inlet for air flow, air passages through the wall housings of the LRU, PCBs were assigned with the heat flux and other boundary conditions were given. Meshing was carried out using polyhedral meshing. Eulerian wall film was selected in the physics. CAD model of single LRU is presented in Figure 7.

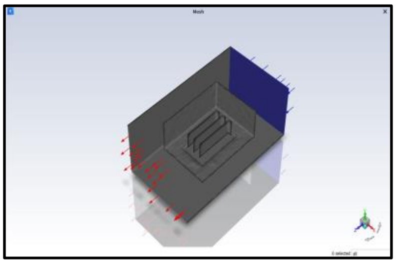

Figure 7: Single LRU - CAD Model

Meshing was carried out using polyhedral mesh. Complete walls and PCBs were modelled using uniform sized mesh which produced significantly accurate results because for single LRU less precision was required. CAD models are presented in Figure 8 showing mesh on PCB cards (left) and mesh of intlet and outlet of air stream (right).

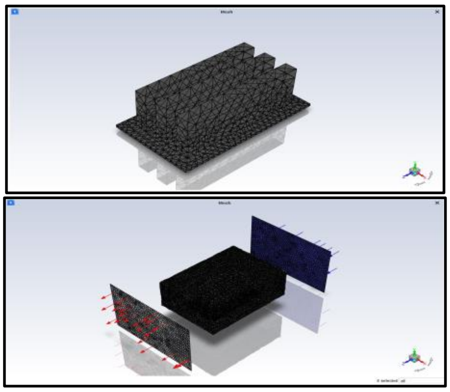

Figure 8: PCBs (left), Meshing Single LRU (Inlet / Outlet & First Enclosure) (Right)

E. Heat Transfer Model - Complete Avionics Bay at Normal Conditions

Complete bay comprises on avionics LRUs stacked up in series (in trays) and in parallel (tower) configuration. One series is stacked up on the other series of LRUs to make a tower configuration. Flow channelling for each series of LRU is dedicated however exclusive LRUs inside a series of LRU gets forced air one after the other. Meshing was carried out using polyhedral mesh. Complete walls and PCBs were modelled using uniform sized mesh which produced significantly accurate results. Figure 9 presents the meshing carried out on one complete bay of avionics.

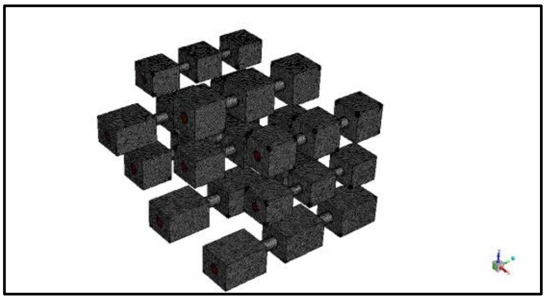

Figure 9: Mesh - Complete Avionics Bay

F. Material & Boundary Conditions

Value of thermal conductivity co-efficient for walls was selected to be 237 W/m.k (for standard aluminum). Air properties were assigned to the fluid at inlet and outlet. PCBs were assigned the value of constant flux heat source which is 40 W/m2 for LRU under consideration. Eulerian Wall Film was on in the Physics to cater for the interaction of air with the housing's walls during modelling of air flow. Inlet boundary conditions defined mass flow rate of the air to be 1.5 kg/m/sec at constant value.

For simulation of black carbon soot deposition inside the LRUs / forced ram air ducting CAD modelling and meshing will remain same as it is already carried out for the normal conditions because we need to compare the results obtained in the form of temperature maintained at the PCBs for the both cases. However, for modelling of effects of black carbon soot there is no direct provision given in the FLUENT which is specifically similar to the case under study. An indirect method to model the deposition of black soot layer on the surfaces of the metallic ducts of ECS was derived based on empirical relations. As deposition of 1g/cm2 thick black soot layer on the conductor walls a decrease in thermal conductivity of 30% is noticed. We have already carried out empirical calculations to show that temperature maintained at the PCBs in case of 1g/cm2 thick layer will be 65 Deg C. Therefore, in our simulations for black carbon soot depositions we will decrease the value of thermal conductivity co-efficient of metal walls by 30% and value of 166 W/m.k will be taken for all LRUs weather in series or parallel configuration in the complete bay case. Remaining parameters such as heat flux generation, inlet velocities of the cooling fluid (air) and configuration/ dimensions of LRUs will remain same.

IV. CFD RESULTS

A. Complete ECS Bay without Black Carbon Soot Depositions

Complete avionics bay of a standard fourth generation fighter or commercial aircraft may have more than 100 LRUs. It is very difficult to model and run simulations for complete avionics system of any aircraft duet to computational limitations. Therefore, only a part of the avionics bay was selected to run the simulations. The modelled ECS avionics bay has 27 x LRUs which have specifications / power ratings & layout similar to left side avionics bay of fourth generation fighter aircraft. These LRUs are stacked in the form of 3 x towers and each tower has 9 x LRUs arranged in 3 x series with 3 x LRUs in each series. Material selection and boundary conditions were same as of simulations run for the series and parallel configurations. In Figure 10 and Figure 11 there are three towers named as left, center and right tower. Top most series in each tower is series 1 followed by series 2 & series 3 in middle and bottom. Results achieved are as following:-

- Highest temperature recorded on the outer wall of the LRU was 45 deg C whereas highest temperature at the PCB inside the LRU was 50 deg C in normal operating conditions.
- Highest temperatures at PCBs were recorded for the last LRUs of series 3 of right and center tower whereas last LRU of series 2 in left tower.
- Temperature range overall was between 38 deg C and 45 deg C which is quite satisfactory range under normal conditions. First LRUs of series 1 in each tower was maintained at lowest temperature which is 38 deg C.

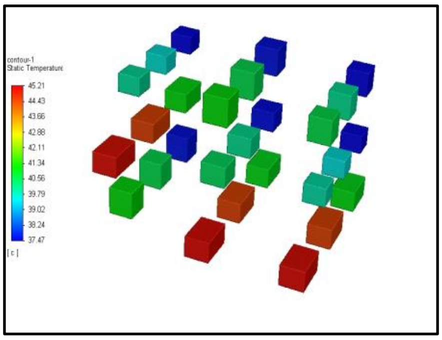

Figure 10: Outside Wall temperatures LRUs without black carbon Soot - Complete Avionics Bay

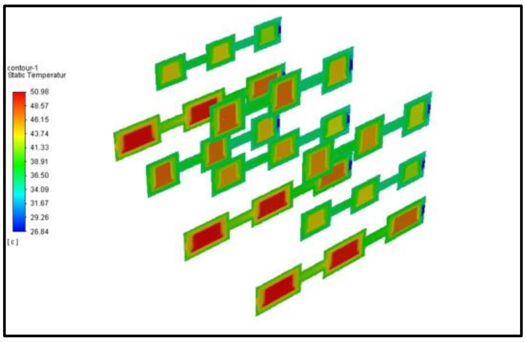

Figure 11: Temperature Profile at PCBs for Complete ECS Bay without Black Carbon Soot Depositions

B. Complete ECS Bay with Black Carbon Soot Depositions

Same set LRUs as simulated in section 6.3 was now subjected to simulation with black carbon soot depositions. In order to simulate the conditions of black carbon soot deposited the thermal conductivity co-efficient of the housings of LRUs was reduced by a factor of 0.3 and the simulation was run and following results were observed:-

- Highest temperature recorded on the outer wall of the LRU was 51 deg C whereas highest temperature at the PCB inside the LRU was 62 deg C. A temperature rise of 12 Deg C or 20% was recorded.
- Highest temperature was recorded at PCBs of second LRU in series 2 of left tower and last LRU of series 3 in right tower.

Figure 12 & Figure 13 depicts detailed temperature profile on LRU housings and PCBs.

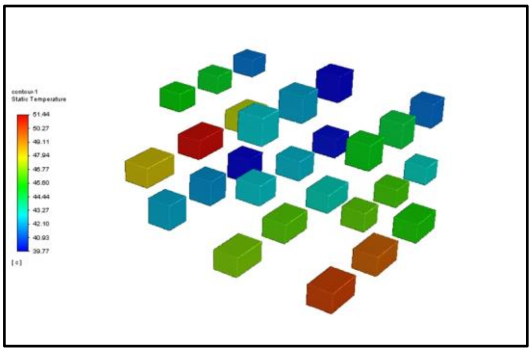

Figure12: Temperature Profile at LRUs with Black Carbon Soot Deposition

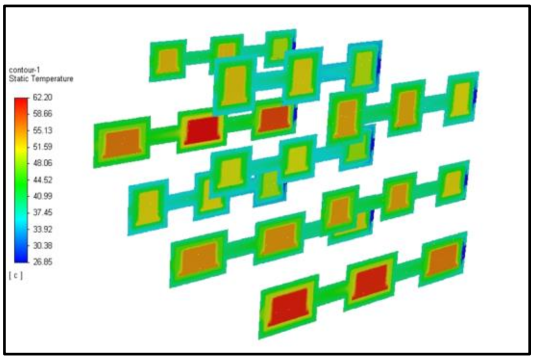

Figure 13: Temperature Profile at PCBs with Black Carbon Soot Depositions

C. Comparison of CFD Results – Without and with Black Soot Depositions

Detailed temperature profile obtained from the simulations run for the normal conditions i.e. without black carbon soot deposition and with black carbon soot depositions are summarized in the table below.

Table 2: Temperature Profiles of LRUs with and without black soot

Series		**Left Tower**		**Centre Tower**		**Right Tower**	
		Normal	**Soot**	**Normal**	**Soot**	**Normal**	**Soot**
Series 1	LRU 1	39	44	46	49	43	50
	LRU 2	42	51	48	50	46	51
	LRU 3	43	52	48	50	46	52
Series 2	LRU 1	46	54	45	49	43	51
	LRU 2	48	60	47	50	45	52
	LRU 3	49	57	47	50	46	52
Series 3	LRU 1	43	49	46	50	46	55
	LRU 2	46	50	50	52	50	60
	LRU 3	47	50	50	53	50	62

V. EXPERIMENTAL FINDINGS

An experiment was designed to find out temperature rise at PCBs of LRUs of avionics due to deposition of black carbon soot layer on the metallic walls of the ECS ducts for subsequent comparison with ANSYS simulation/ validation.

VI. EXPERIMENTAL SETUP & CONTROL PARAMETERS

Following sequential steps were taken to establish the experimental setup for execution of experiment runs-

A. Modelling of LRUs of Avionics

- 9 x LRUs of different systems installed in an aircraft were removed from aircraft after its continuous operation since last 500 hours of flying.
- LRUs were examined for presence of black carbon soot and it was confirmed that each LRU originally have deposits of black carbon soot in its ECS ducts when it was removed from the aircraft.
- Black carbon soot was removed with a brush from all accessible surfaces after removal of rear panels of the LRU housings and collected in a weightless plate.
- Mass of black carbon soot thus extracted from each LRU was measured using a digital weight scale and recorded against each LRU.
- Mean of the black carbon soot depositions found per surface area were calculated. It was found to be 3g/m2.

B. Heat Generation at PCBs

Since LRUs were removed from the aircraft an external power source of 28 V DC was required to energize the avionics LRUs up to the maximum power ratings. Thus, a lab held DC power source was used to energize the LRUs so that PCBs can function to dissipate heat. LRUs were left to operate continuously for three hours so that a constant heat flux condition can be obtained at the heat source.

C. Temperature Sensing Inside LRUs

Thermocouples Omega SA1-RTD were pasted on one PCB of each LRU to sense the temperature at all times during the experiment. The temperature readings were read on handheld digital metre Omega HH804U.

D. Layout of LRUs & Source of Forced Air

LRUs were assembled on a platform & ECS ducting were fabricated to join the inlets of forced ram air of these LRUs in a series & parallel configuration. A controlled source of air (air blower) was used to throw air into this air channel.

E. Source of Black Carbon Soot

BEG 2000 PALAS was used to generate desired thickness of carbon soot layer by maintaining constant flux of carbon soot for experiment run. Figure 14 presents the BEG 2000 PALAS particle generator used during experimentation part.

Figure 14: BEG 2000 PALAS particle generator

VII. EXPERIMENT RUN

First run was under normal conditions in which LRUs were subjected to mass flow rate of 2kg/sec as per rated mass flow rate of ECS. Inlet temperature of forced ram air was set at 25 Deg C. Temperature at PCB after its continuous operation for three hours was recorded using thermocouple SA1-RTD. Inlet ram air was carried from the open source without any black carbon soot particles. Temperature readings after interval of 30 minutes were recorded for next 5 hours of operation of LRUs.

Whereas in second run of experiment particle generator was plugged in at inlet source and it was set to produce black carbon soot at rate of 1g/minute. The particle generator was allowed to run for 10 minutes. It will allow deposition of carbon soot layer on each of the 9 x LRUs with average thickness of 1g. Whereas, the LRUs placed in front of the air stream will have naturally more deposition of the black carbon soot. However, it holds good for the actual ECS bay as well. Therefore, a significant similarity has been achieved in design of the experiment. Temperature readings were recorded for 10 minutes at interval of 1 minute.

In third run of trial the particle generator was stopped. LRUs were turned off and allowed to cool down to zero. After all, LRUs were reset a continuous operation for 5 hours was carried out with deposited black carbon soot and temperature at PCBs were recorded with interval of 30 minutes. Complete schematic is attached as figure below:-

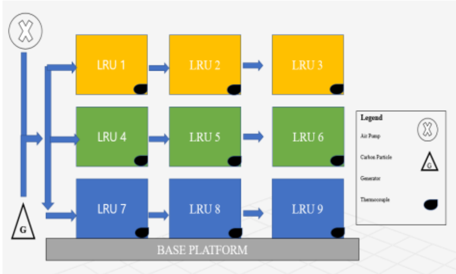

Figure 15: Scheme / Layout of Experiment

VIII. RESULTS OF EXPERIMENTS

Following results were obtained for the experiments conducted:-

- Highest temperature reached on PCB inside LRU was recorded to be 59 Deg C without black carbon soot deposition after continuous operation of 5.5 hours at LRU 9.
- Highest temperature reached on PCB inside the LRU was recorded to be 66 Deg C with black carbon soot deposits of 1g/cm2 at after continuous operation of 5.5 hours at LRU 9.
- Average temperature rise of 7 Deg C i.e. 11% was recorded for LRU 3 6 and 9.
- Lowest temperature maintained without black carbon soot deposition was recorded to be 49 Deg C after continuous operation of 5.5 hours at LRU 1.
- Lowest temperature maintained with black carbon soot deposits was recorded to be 55 Deg C at LRU 4 whereas LRU 1 was maintained at 56 Deg C after deposition of black carbon soot.
- In case of lowest temperature, a rise of 6 Deg C was observed i.e. 11%.

A. Comparison Empirical, CFD & Experimental Results

Comparison of results obtained from each approach is shown in below table 3-

Table 3: Comparison of results

Observations	Experimental Approach (Deg C)	Empirical Approach (Deg C)	ANSYS/ FLUENT Results (Deg C)
Temperature at PCBs without black soot deposition	59	65	54
Temperature at PCBs after black carbon soot depositions	66	73	62
Net Rise in Temperature at PCBs due to black carbon soot depositions	7 (10.7%)	8 (11%)	8 (11%)

IX. CONCLUSION

Keeping in view detailed analysis and results of empirical, experimental and simulation approaches we can conclude findings of this research as following:-

- Black Carbon Soot deposits cause 11% rise in temperature of aircraft avionics ECS.
- Reliability and performance of aircraft avionics is reduced by up to 30% due to consistent overheating.
- Overheating of avionics due to Black Carbon Soot can cause mechanical failures such as buckling of LRUs housings because of thermal stresses generated due to overheating.

- Power ratings of avionics and their location in the ECS bay are important design factors to prevent overheating of avionics and thus require deliberate optimization during design.
- The last LRUs in a series configuration of ECS will comparatively be more overheated because of black soot phenomena as compared to the first LRU in the series.
- Closed circuit ECS forced ram air undergoes obstructions due to contaminations, degradations and depositions caused due to environmental factors (black soot, corrosion, dust and dirt etc.) & effective mass flow rate is reduced downstream in ECS.
- Active and Passive Measures to prevent ECS from black carbon soot depositions are not included in SPMPs.

X. RECOMMENDATIONS

Keeping in view key findings of this research following recommendations are proffered:-

- Avionics LRUs should be designed to have a temperature sensing probe installed inside the LRU housings (at PCB boards) so that early warning of overheating is given in the cockpit if any single LRU is operating under overheated conditions.
- One Time Inspection (OTI) of commercial & fighter jet fleets may be carried out by operators for inspection of Black Carbon Soot Depositions in Avionics LRUs.
- Routing of ram air in forced convective cooled avionics should not include direct contact of air with the organic substances/ materials (PCB boards, wires , cables etc.) instead forced ram air should remain in closed circuit from entry till exit from the avionics bay to avoid influx of carbon particles / soot along the stream.
- Configuration/ layout of avionics LRUs in ECS bays should be optimized with respect power ratings of avionics LRUs.
- Alternate designs of ECS such as electrically operated air pump must be given preference over ram air extraction from the engine compressor stage to avoid loss of engine efficiency. Furthermore, such designs may incorporate dedicated sources of forced air (air pumps) for each series of avionics LRU in an avionics bay.
- SPMPs should include removal of avionics LRUs from the aircraft every 500 hours of flying for detailed inspection of ECS duct routings for deposition of black soot & other contaminants. If found black soot should be cleaned using alcoholic solvents from all accessible parts of avionics LRUs.
- Avionics LRU housings designed for forced convective cooled avionics should not have walls with permanent joints instead walls should be removable to allow maximum visual access to ECS ducting allowing inspections / cleaning during SPMPs.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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