# AIRCRAFT FLIGHT TRIALS AND DESIGN ISSUES FOR THE AVIONICS COOLING SYSTEMS ON THE EH101

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## Abstract

This paper gives an overview of the Avionics Cooling System (ACS) developed for the Utility variants of the EH101 helicopter. The complex design issues faced in designing systems that must comply with avionics flight and mission criticality requirements across an extensive environmental operational envelope are addressed.

This paper discusses the design criteria and subsequent rig and flight test philosophies for aircraft clearance, and evolution of the design solution from development through to production for compliant flight operations both in continuous icing and through to ISA +35°C.

A summary of aircraft flight trials and the methodology used in measuring and qualifying the ACS for flight is presented. The problems encountered and design issues faced after flight testing showed that negative external pressure coefficients forming around the ACS air inlet caused a significant reduction in cooling capacity is also discussed.

The paper concludes by discussing the lessons learnt and current design practices and tools used in the design of Environmental Controls Systems, including the use of Computational Fluid Dynamics, fluid flow simulation packages and analytical models to predict system performance and de-risk potential design issues. The result has been to drastically reduce the amount of post design activities, and subsequent rig and aircraft flight testing required to achieve qualification of the production solution.

## Units, Symbols and Abbreviations

### Units and Symbols

| | |
|---|---|
| °C | Degrees Celsius |
| hr | hour |
| kg | kilo grams |
| kW | kilo Watts |
| l/min | litres per minute |
| m/sec | metres per second |
| PSIA | Pounds per Square Inch Absolute |

### Equations

[1] $$P = 0.5\gamma P M^2 C_P + P$$

| | | |
|---|---|---|
| *Where* | $P$ | Pressure at $C_P$ zone (PSIA) |
| | $\gamma$ | Ratio of specific heats of air |
| | $P_0$ | Ambient pressure (PSIA) |
| | $M$ | Aircraft mach no. |
| | $C_P$ | Coefficient of pressure |

### Acronyms and Abbreviations

| | |
|---|---|
| ACP | Air Cycle Pack |
| ACS | Avionics Cooling System |
| ARINC | Aeronautical Radio Incorporated |
| ASMC | Aircraft System Management Computer |
| CFD | Computational Fluid Dynamics |
| CSH | Canadian Support Helicopter |
| DMDS | Digital Map Display System |
| ECS | Environmental Control System |
| EMC | Electromagnetic Compatibility |
| FAR | Federal Aviation Regulations |
| FCC | Flight Control Computer |
| FWD | Forward |
| GRS | General Requirement Specification |
| HIRF | High Intensity radiated Fields |
| ICD | Interface Control Document |
| JAR | Joint Aviation Requirement |
| KIAS | Knots Indicated Airspeed |
| LWC | Liquid Water Content |
| OAT | Outside Air Temperature |
| PP | Pre-Production |
| RAF | Royal Air Force |
| SGU | Symbol Generator Unit |

## SECTION 1 – Introduction and Background Information

The AgustaWestland EH101 rotorcraft is a medium lift, multi-role, all weather capability vehicle.

Figure 1. EH101 Merlin Mk3

The ACS installed on Utility variants of the EH101 helicopter provides a supply of outside ambient air to cool the avionics LRUs located in two avionics cabinets (a port installation and a starboard installation). Air is exhausted from the avionics cabinets overboard through the roof of the aircraft.

Electrically powered fans are configured in a parallel arrangement. The type of fan and number required is dependent on the heat load to be cooled and varies between EH101 aircraft. Typically a two or three fan arrangement is utilised where one or two fans run continuously whilst the other is available should either of the other fans fail. The outlet of each fan is coupled to a non-return valve, which serves to isolate the outlet of the non-operational fan, thus preventing a loss of cooling flow through the redundant fan.

Cooling air is provided to both avionics cabinets via a system of ducts and plenum chambers within the cabinets. Cooling air is blown directly through the enclosures of those LRUs that are force cooled. The flow of air is regulated by means of blanking holes in throttle plates located underneath the LRUs (i.e. upstream). Additional cooling air is allocated for non-forced cooled units and is metered through throttle plates in the shelf plenums exhausting into the avionics cabinet.

The depiction of the ACS installed on Utility variants of the EH101 helicopter is shown in Figure 2.

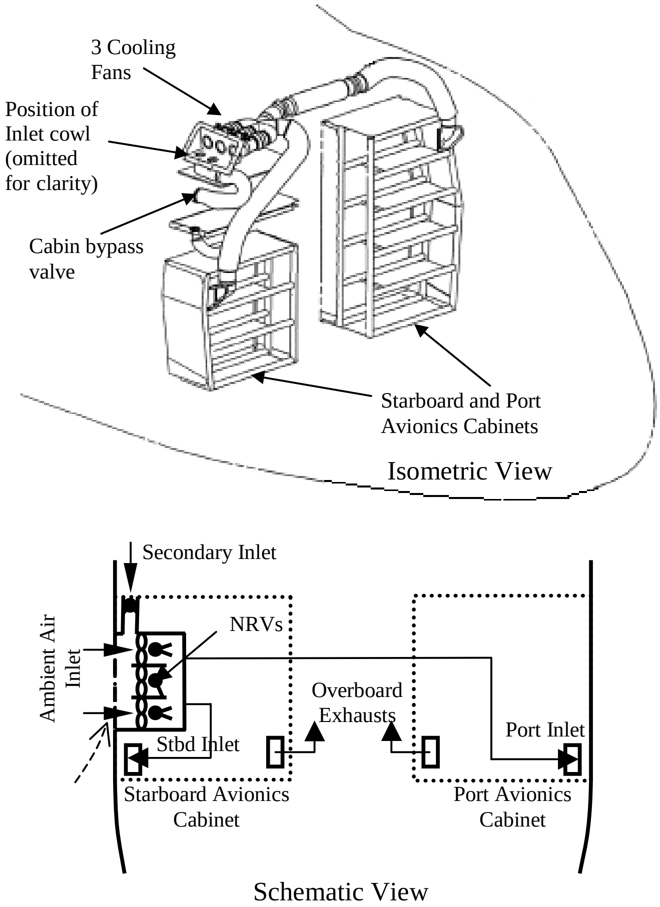


Figure 2. Isometric View and Schematic View of the EH101 Avionics Cooling System

### Environmental Considerations

**Icing** The ACS for Utility variants of the EH101 is designed to allow for known entry and continuous operation into icing conditions. In order to compensate for blockage of the main external inlet that may occur with ice, a secondary inlet referred to as the ‘anti-ice cabin bypass valve’ was originally incorporated into the design of the ACS for the Utility variants. The bypass valve is not included in aircraft where clearance is required only for inadvertent entry into icing conditions.

The cabin bypass valve serves as an alternate inlet for cooling air should the external inlet become blocked. A simple non-return valve is employed, that opens when a differential pressure across it exceeds a set point (cracking pressure) allowing air to be drawn from the aircraft cabin as well as the external inlet in the case of partial blockage, or solely from the aircraft cabin in the case of total blockage of the external inlet.

The initial thought process of the anti-ice cabin bypass valve was for the valve to open only at low OATs (i.e. in icing conditions). This would limit the level of noise pollution that would inevitably occur with drawing air in from the cabin. The cabin conditioning ACP is a role-fit option for Customers, and at elevated OATs the cabin temperature could potentially be above OAT. A valve that opens only a low OATs would therefore ensure that air at potentially higher cabin temperatures was not used for cooling of the avionics LRUs.

**Sand and Dust** An active decision was made not to include a designated defence against the ingress of sand and dust into the design of the ACS. The high position of the ACS air inlet (ref. Figure 4) and the equipment's conformance with the Dust and Sand regulations invoked in the EH101 GRS were contributing factors to this decision. The inclusion of filters and cetrisep's was investigated but concluded that such items did not provide a greater defence against sand and dust particles than what is inherent in the design of this system. The many changes in the airflow direction plus the reduction in airflow velocity through plenum chambers allow sand particles to drop out up stream of the LRUs. Furthermore the benefits of such items when compared with their negative affects, such as pressure drop and subsequent detrimental affect on fan performance, increase in weight and maintenance inspections, did not justify inclusion into the system.

**Water Ingress** As with Sand and Dust the ACS for Utility variants of the EH101 do not include a designated defence against the ingress of water for the same reasons outlined in the section above. The many changes in the airflow direction plus the reduction in airflow velocity through plenum chambers allow water droplets to drop out up stream of the LRUs.

**EMC** The ACS inlet incorporates a honeycomb filter for HIRF protection.

## Design Aim of the ACS

The design aim of the avionics cooling system is to provide a flow of cooling air to satisfy three basic requirements:

*Cooling air is provided directly to all force cooled LRUs located within the avionics cabinets either in accordance with the equipment vendors' own requirements or in the absence of this, ARINC 600.*

*Sufficient cooling air is provided to the avionics cabinets such that the temperature of the inlet air does not exceed +55°C (the maximum air inlet temperature for continuous operation of all forced cooled LRUs).*

*Sufficient cooling air is provided to the avionics cabinets such that the temperature of the exhaust air does not exceed +70°C (the maximum ambient temperature for continuous operation of all LRUs).*

In order to satisfy the three basic requirements, temperature and pressure measurements are recorded throughout each avionics cabinet. To quantify the volume of airflow delivered to the LRUs the pressure measurements are converted to airflow using LRU pressure versus airflow calibrations.

Where testing cannot be carried out throughout the entire temperature envelope, test results are extrapolated on a 1:1 basis taking into account the effects of air density and pressure with varying OAT.

## ACS Detail Design

Although the overall design philosophy for the ACS is common across Utility variants, the detail design of each individual variant system is different. Each variant has a specific avionics fit and arrangement. As a result, total heat load and cooling requirements, and therefore flow distribution varies significantly between EH101. For example, the EH101 CSH has a total of 8 forced cooled LRUs and a total heat load of 926W. Whereas the EH101 Merlin Mk3 has a total of 11 forced cooled LRUs and a total heat load of 1522W respectively.

The distribution of air is regulated by means of blanking holes where the arrangement of the blanking holes is referred to as the 'throttle configuration' and is specific to each particular variant. Historically, preliminary detail design of the ACS (i.e. throttle configuration, fan size, number of fans required) was determined through extensive rig testing. In order to establish the correct distribution of airflow a full mock up of the ACS would be assembled with the avionics LRUs represented by 'dummy' wooden boxes, calibrated to represent the pressure loss/flow characteristic of the LRU as specified in the equipment ICD. Through rig testing a final throttle configuration could be defined for aircraft build.

The ICD cooling requirements of the avionics LRUs are often not consistent with heat load; with ARINC 600; or with the environment. The mechanical aspects of the design of the LRU to comply with the specified requirements were frequently not well defined. As a result, an aircraft build standard (defined after significant rig testing) that theoretically would require little or no modification after aircraft testing often required adjustment. Incorrectly defined characteristics of the LRU would lead to imbalances in the system and often resulted in significant re-working of the system post aircraft build. Consequently calibration of the actual LRU boxes and mounting trays is now common practice.

**Avionics Inlet Cowl**

The position, size, orientation and shape of the effect of the air inlet cowl has a significant effect on cooling performance of the ACS.

The original ACS inlet cowl as on the Pre-production EH101 aircraft is depicted in Figure 3. The PP aircraft utilised a twin fan arrangement and were qualified to operate in temperatures up to ISA + 23°C. The PP aircraft were qualified only for inadvertent entry into icing conditions. Although the PP aircraft were not qualified for continuous operation in icing conditions, a downward facing scoop was designed to limit ice accretion in inadvertent entry and also allow for future extension to the EH101 operating envelope.

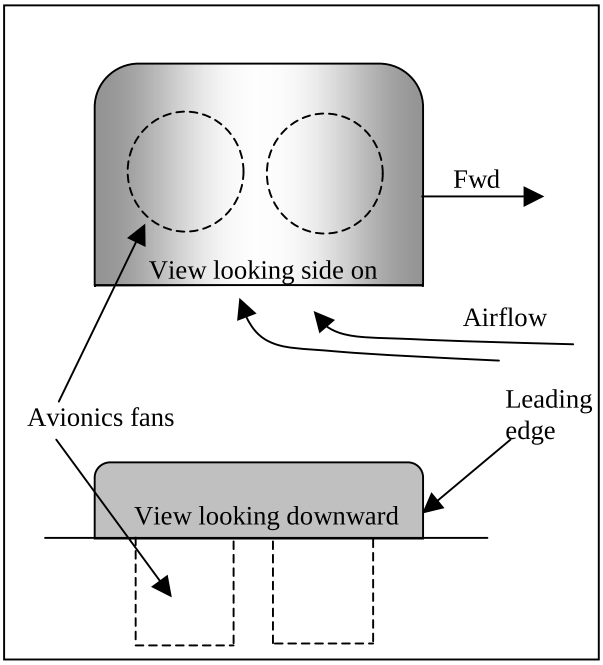


Figure 3. Pre-production ACS Inlet Cowl

For production aircraft the operational temperature release was required to be extended to ISA + 25°C for the EH101 CSH and following this ISA +35°C for the EH101 Merlin Mk3. Along side the increase in temperature envelope each aircraft was required to be fully operational in icing conditions.

Development testing had indicated that the system had sufficient margin to allow for the operational temperature release to be increased, dependent on the total heat load requirement and detail design. Preliminary analysis and development flight testing of the PP cowl had also demonstrated that a drop in cooling airflow was evident in forward flight, having an increasing detrimental affect with increasing forward airspeed. This was as a result of the presence of suction effects on the intake relative to the system outlet. The ACS is a high flow low pressure system and as a result system performance can be drastically affected by outside pressure coefficients. However, although a reduction was evident, testing had demonstrated that the system performance margin was sufficient to overcome these detrimental aerodynamic effects.

Although the PP inlet was designed to allow for a release of operations in icing conditions for development flight trials the production aircraft inlet would still require further assessment, particularly the leading edge profile. It was believed that ice would accrete and build up on the leading edge of the inlet. The inlet is positioned in front of the no. 3 engine and therefore shedding of the ice could compromise the engine and possibly the main and tail rotors. The position of the inlet is common across all Utility EH101, dictated by the common avionics cabinets position, and space constraints such as footsteps, other equipment, structural joins etc meant that moving the position of the inlet was not an option. Therefore, in order to allow for operations in continuous icing conditions, a modification to the inlet was required. The leading edge was modified (ref. Figure 4) such that supercooled water droplets would not impinge directly on the fairing surface. This would allow for operations in icing conditions without introducing further weight, cost and the complexity involved with a heated intake.

**Development Testing**

Significant rig testing was carried out with the new inlet to ensure that system performance was not adversely affected by the reshaped cowl. A small fall in performance was noticed and was attributed to the reduced effective air inlet area. Further rig testing was performed to assess the operation of the anti-ice cabin bypass valve. The inlet was blocked to simulate ice accretion and a valve cracking pressure defined by assessing the point at which the system no longer delivered the required cooling airflow. The effects of air temperature and the effects of the predicted suction effect at the inlet were taken into account in the analysis.

Rig testing concluded that the twin fan ACS performed adequately with sufficient margin (taking into account the fall in performance at forward airspeeds) to allow for an operational release to ISA +25°C for the EH101 CSH. To allow for an ISA +35°C release for the EH101 Merlin Mk3 a three-fan arrangement was considered necessary. In this arrangement two fans are operational at anyone time resulting in increased airflow. The same basic inlet cowl was used but scaled up to accommodate the additional fan.

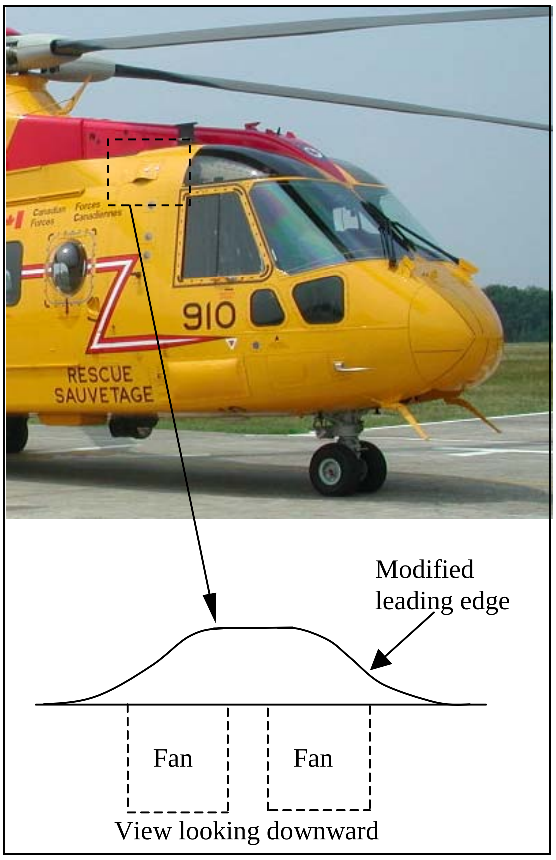


Figure 4. EH101 CSH with the re-shaped ACS inlet cowl

**SECTION 2 - Aircraft Flight Trials and Design Issues**

Aircraft testing of the CSH was performed in 2001. Although a build standard with sufficient margin to allow for an ISA +25°C release had been defined through rig testing, actual aircraft test results showed otherwise. The LRU cooling requirements were only achieved with the aircraft on the ground and in the hover, and fell short of the requirement in forward flight. The aerodynamic effects on the new cowl and subsequent impact on fan performance was far more extreme than had been envisaged. The fall in performance at forward airspeeds with the new cowl was significantly more than that experienced in development flight testing with the PP cowl. This can be seen in the results detailed in Appendix A of this paper.

The ACS provides air to cool flight critical equipment and as a result the performance of the ACS can impose significant OAT operating limitations, airspeed limitations and limitations to the flight envelope. With the ACS of EH101 CSH operating in this way a limited temperature release of only ISA +15°C could initially be given.

During this time aircraft testing on the EH101 Merlin Mk3 ACS was also performed. A significant fall in performance at forward airspeed was again evident but was more detrimental in the three-fan arrangement. With the ACS of EH101 Merlin Mk3 operating in this way a limited temperature release of only ISA +10°C could initially be given.

During initial flight testing two other observations were evident. The anti ice cabin bypass valve was opening in flight with no blockage to the inlet and secondly, repeatability of system performance in full production was found to be of concern. Where development testing was performed on only one aircraft of a given variant type, testing of the production aircraft was carried out on a number of aircraft and often showed varying results between aircraft with apparent identical build standard.

**Investigation**

To improve system performance and achieve the full aircraft temperature releases of ISA +25°C for the CSH and ISA +35°C for the Merlin Mk3 a design investigation was launched.  At this time a fluid flow simulation package (Flowmaster) was introduced to effectively model the system. This package allowed for sensitivity studies for equipment layout, throttle configuration and predictions for flight for various modifications of the inlet.

Aircraft testing had already showed that the effects of the negative pressures at the inlet were more influential on system performance with the new cowl than with the PP cowl. It was for this reason that the anti-ice cabin bypass valve was opening prematurely. The suction effect at the open inlet relative to the cabin pressure was greater than the simulated blockage to the inlet in the ground static case. Therefore in fast forward flight the bypass valve was permanently open, aiding in system performance. Aircraft testing of the CSH ACS was performed with both the valve closed and the valve allowed to open. With the valve operating as intended (i.e. closed) the ACS was unable to deliver sufficient airflow to support a temperature release of ISA +15°C (as with the bypass valve open). Although the bypass valve was not designed to open in higher OATs it did allow for the highest temperature release of the aircraft.

A range of ACS's on different aircraft was assessed to discover why results varied between different aircraft of the same variant. It was observed that the build standard of the avionics cabinets was inconsistent across the fleet. Two main areas of inconsistency were incorrect throttling of the force cooled LRUs, this was attributed to human error, and secondly to the lack of caulking material around tray seals and the corners of riveted assemblies, resulting in a significant amount of airflow lost through leakage's. Shelf/ducting leakage adversely affects the upstream pressure of the forced cooled LRUs which are primary flight critical LRUs on the EH101. Whilst leaks would aid in the cooling of the convective cooled LRUs, its volume could not be quantified and as a result could not be included in analysis.

In order to reduce the volume of airflow lost through shelf leakage's a modification was introduced where gaps in the shelves were caulked. A re-throttling exercise was also carried out in order to enhance the system in light of this modification. This exercise showed significant improvement, particularly for the CSH variant. The systems were then re-tested with both the bypass valve allowed to open and with the bypass valve closed, and emphasised the influence of the cabin bypass valve. Results detailed in Appendix A, Table 1 and Table 2 demonstrates that with the bypass valve open a considerable increase in flow is achieved, particularly in forward flight where approximately an 80% increase is measured. Analysis concluded that the marked increase in flow with the by-pass open, more than compensated for the resultant increase in delivery temperature to the LRUs.

In the case of the CSH variant all force cooled LRUs received 97% of their required cooling flow. Therefore the maximum temperature release of ISA +25°C was given with the cabin bypass valve allowed to remain open. Although this was not the original design solution of the bypass valve (and would not be acceptable for a civilian application due to the noise pollution) it was considered acceptable for a military application where headwear will be worn.

Although caulking the gaps in the shelves showed improvement with the EH101 Merlin Mk3, due to the much higher cooling requirement the improvement was only significant enough to warrant an ISA +15°C temperature release, significantly short of the ISA +35°C design aim. Alternatively a higher OAT temperature release could have been given but a forward airspeed limitation imposed. The suction effect at the inlet relative to the system outlet, and subsequent adverse effect on fan performance increased exponentially with aircraft forward airspeed (this can be explained by equation 1 where $P$ is relative to $M^2$). Furthermore, analysis of the anti-ice cabin bypass valve demonstrated that as the aircraft forward airspeed increased (and therefore the pressure at the inlet decreased) the ratio of cabin air to outside ambient air increased in favour of cabin air. However, as more air was drawn through the bypass valve the flow of air 'choked'. For these reasons the fall in system performance is more evident at higher airspeeds than at lower airspeeds. Therefore a higher OAT temperature release could have been given but a forward airspeed limitation imposed.

To avoid limiting the aircraft to operations in temperatures less than ISA +15°C or to impose an airspeed limitation a solution was required where total system pressure loss and flow characteristics were maintained at forward airspeeds. Furthermore, in order to achieve the full temperature release of ISA +35°C the cabin bypass valve had to remain closed for the following reason:

The Merlin Mk3 is designed to operate in OATs of +50°C. Experience has demonstrated that the cabin temperature can be +10°C above OAT (in the worse case assuming no role-fit ACP is fitted). With air being drawn in from the cabin an air inlet temperature greater than the maximum allowable +55°C would be experienced (particularly at higher airspeeds where the ratio of cabin air to outside ambient air increased in favour of cabin air). Therefore a +50°C OAT temperature release could only be given to the Merlin Mk3 with the bypass valve closed. The maximum allowable temperature release with the cabin bypass valve open would therefore be limited to +45°C (assuming a 50:50 ratio of cabin air to outside ambient air) regardless of the volume of airflow delivered.

**Modification to the Inlet Cowl**

A design study was carried out to modify the existing inlet in order to recover system pressure at forward airspeeds.

A number of design ideas were considered with a view to achieve ram recovery in forward flight. A forward facing cowl would achieve most noticeable results, however a forward facing cowl is bound to accrete ice. This is acceptable for aircraft with a limited icing release, and is the solution adopted for Civilian variants of the EH101. The Civil variant of the EH101 was also the subject of development to extend the operational temperature from ISA +23°C to ISA +35°C. The EH101 Civil ACS development is discussed later in this paper. The Merlin Mk3 has an icing release for continuous operations in icing and therefore a forward facing cowl was not a viable solution. Therefore an alternative way of increasing the external pressures at the inlet to compensate for system losses in forward flight was required.

The inlet was redesigned to incorporate an aerodynamic dam under the inlet cowl (ref. Figure 5) with a view to increase pressure at this point. With the introduction of the aerodynamic dam the performance of the ACS significantly improved in forward flight cases. However, ground performance reduced slightly as the addition of the aerodynamic dam reduced the effective area of the intake. The airflow around the aerodynamic dam also interfered with the static vent located below the inlet cowl in rapid ascent/descent. This was unacceptable. The dam would also be susceptible to ice accretion. As a result a further redesign of the cowl was recommended where the advantages of the aerodynamic dam could be realised without adversely affecting the static vent or ground performance.

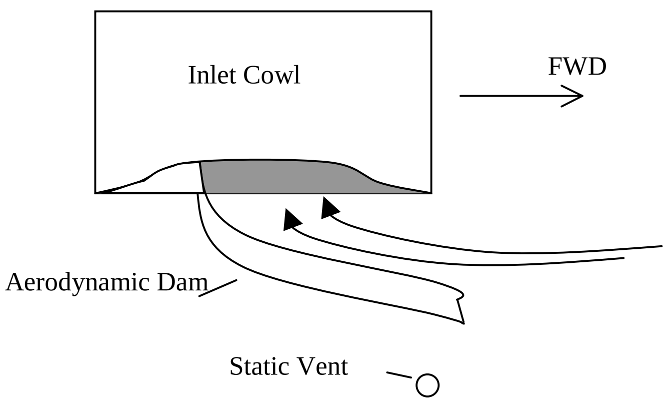


Figure 5. Aerodynamic dam fitted to the original ACS inlet cowl

A second iteration of design was developed. The dam was shortened so that the forward tip of the dam was aft of the static vent. The forward profile of the cowl was not changed (Figure 6, View 2) as this was designed to limit ice accretion. The aft profile was made more angular to increase the cross sectional area of the inlet and the aft section of the cowl was also extended downward (Figure 6, View 1) to provide a forward facing section of the inlet. The aerodynamic dam was positioned inside the cowl to reduce ice accretion.

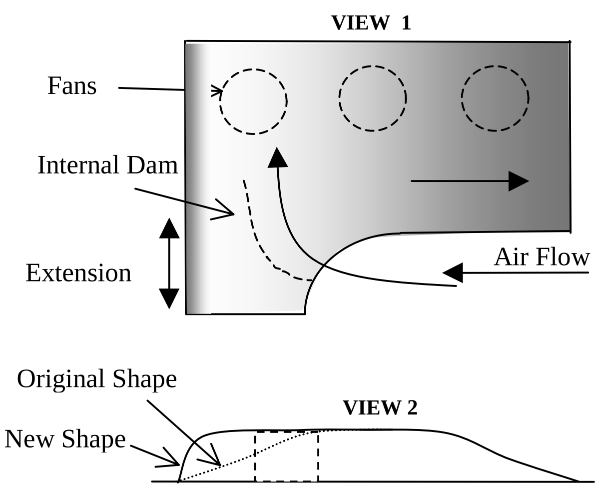


Figure 6. ACS Inlet Cowl Development

Flight testing of this design showed that although considerable improvement was seen a fall in performance at higher forward speeds (40KIAS+) was still evident. It was believed that the cause of this drop in performance was the nose down pitch attitude of the aircraft at higher speeds. Under these conditions, the main section of the cowl shadowed the forward facing section of the cowl so that the internal dam did not see any direct air flow.

The final/optimal standard of cowl for all environmental aspects was reached with an increased airflow area to reduce pressure drop and an extended forward facing section to ensure the internal dam was in the air stream with the aircraft in a nose down pitch attitude (ref. Figure. 7).

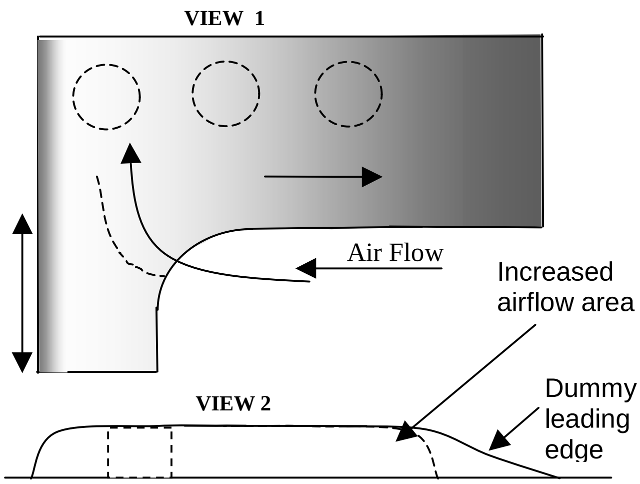


Figure 7. Final/optimal standard of ACS inlet cowl

Although a significant improvement was demonstrated the increase in airflow with the existing fans was not enough to allow a full ISA +35°C release. Therefore higher performance avionics fans already in use on the MMI EH101 were utilised and the ISA +35°C release was given. This modification was incorporated in-line with an upgrade to the avionics LRU build standard (the introduction of the DMDS) that resulted in increased heat load.

The significant improvement in ACS performance on the Merlin Mk3 can be seen in Table 2. Although a fall in performance in fast forward flights is still evident the effect is considerably less that that seen with the original inlet cowl, an improvement from a 50% reduction to only a 9% reduction.

## EH101 Civil

The Civil variant of the EH101 was also the subject of development to extend the operational temperature release from ISA +23°C to ISA +35°C. Due to the EH101 Civil only being qualified for inadvertent entry into icing conditions a forward facing cowl was considered suitable (ref. Figure 8). A secondary air inlet aperture was included on the underside of the inlet cowl, incorporated in the design for both an extra air inlet area and to act as a water drain. Flight testing of the EH101 Civil demonstrated that the forward facing inlet cowl was successful in assisting the ACS to deliver cooling airflow to the LRUs and achieve an ISA +35°C clearance. However, the position of the avionics cooling inlet on the aircraft and the forward facing aspect of the inlet combined with it's function - to direct airflow into the ACS, combine to result in a feature which is bound to accrete ice in the event of the aircraft inadvertently entering icing conditions. Therefore analysis was carried out to ensure that blocking to the inlet in icing conditions would not adversely affect cooling of the avionics LRUs.

With the forward facing cowl, airflow to the avionics cabinet was found to increase with increasing forward airspeed, which consequently would be the worst case icing condition. In this condition flight testing had demonstrated that it would be possible to lose 63% of flow and still meet the requirements of all force cooled LRUs to support an ISA +35°C release.

Analysis was conducted using the fluid flow simulation package – Flowmaster, and concluded that in excess of 90% of the forward facing inlet could have blocked before the airflow to the system reduced by as much as 50%. The secondary air inlet aperture on the underside of the inlet cowl was kept fully open in the analysis as it was believed that it was unlikely that this section would accrete ice due to the non forward facing aspect of this section, and the nose down pitch attitude of the aircraft in the cruise condition.

The Rotorcraft Flight Manual prohibits dispatch or entry into known icing/snow/freezing rain conditions and requires that if these conditions are entered inadvertently they must be vacated as soon as possible. However, the level of ice accretion which may occur during such an inadvertent entry into icing conditions needed to be considered to evaluate if the inlet would become more than 90% blocked.

The majority of inadvertent encounters the level of ice accretion would be low and therefore, when combined with the reduced OAT, would not compromise the cooling of the avionics. The EH101 Basis of Certification and FAR Advisory Material however make recommendations for the most severe condition that may be encountered. Therefore analysis was carried out assuming 20 minutes in maximum continuous icing. The time period of 20 minutes was taken from JAR advisory material (allowing 5 minutes of crew recognition of the icing condition). Considering the icing condition, it was thought that the most severe inadvertent entry would most likely occur between -5°C and -10°C. Above this temperature it was expected that not all of the liquid water would freeze and below this temperature the liquid water content (LWC) decreases. A pessimistic calculation (based upon the known ice accretion rate exhibited by the military EH101 ice accretion meter) suggested that in cruise conditions (approximately 120 knots) with an LWC of 0.6g/m$^3$ approximately 35mm of ice would grow in 20 minutes and would be contained within the forward edge of the inlet. Although an accretion of 35mm of ice would have significantly blocked the intake it was believed that it would not result in 90% blockage, and in turn cause the system airflow to fall below the force cooled LRU requirement. Therefore an operational temperature release for ISA +35°C was given for the EH101 Civil.

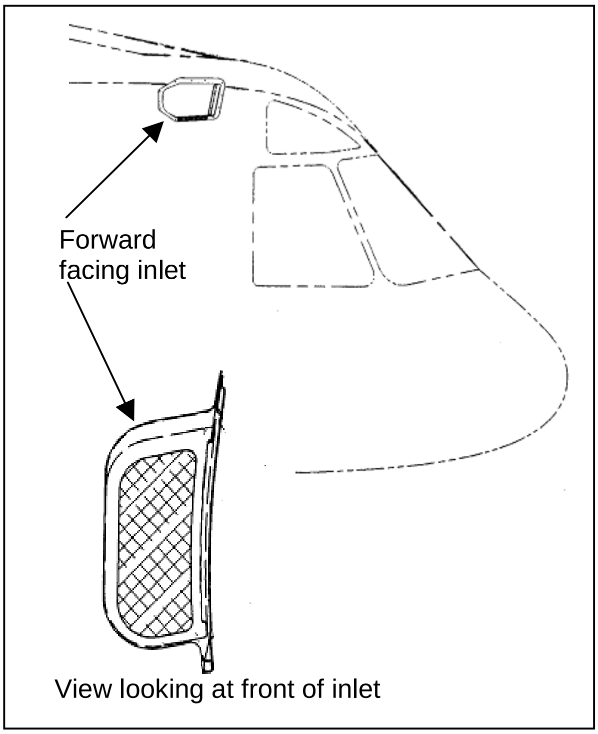


Figure 8. Forward facing ACS Inlet on the EH101 Civil

## SECTION 3 – Lessons Learnt and New Practices

The evolution of aircraft has seen the use of electronic equipment increase rapidly in recent years and the operating temperature environments have increased considerably. Consequently environmental control systems, both crew conditioning and avionics cooling are considered higher priority than in the past. Historically where less design emphasis was given to environmental control systems, and with a lack of design tools available potential design issues were at times not easily evident prior to aircraft testing. The effects of design modifications could not accurately be assessed without rig or aircraft testing, which was time consuming and expensive. A number of design tools and practices have now been employed to increase efficiency and allow for accurate detail design of systems to be defined prior to aircraft build.

### Design Tools

The use of Computational Fluid Dynamics and fluid flow simulation packages has allowed for accurate prediction of system performance, external influences and interactions. Potential design issues can now accurately be assessed and be taken into account in the preliminary design of the system. The result has been to significantly reduce the amount of drawing change, mod action and rig and aircraft testing required.

### Acceptance Test Procedures

The inconsistency in build standard of the avionics cabinets was an issue that required further consideration. Although measures were put in place with a view to seal the cabinets and reduce the amount of airflow lost through leakage's it was still inherent in a design of that nature that a certain amount of airflow would be lost, and the quantity would vary between cabinets. The accuracy of throttle configuration of LRU mounting trays was also subject to human interpretation and as such potentially an area where inconsistencies may lie. As the ACS supplies cooling to flight critical equipment it was paramount that each system must operate as designed. For these reasons a modification was incorporated to introduce permanent pressure tappings to the avionics cabinets. This would allow for production Acceptance Test Procedures (ACP) and in-service validation of the system post LRU changes, where pressures throughout each cabinet could be evaluated against pre—determined 'on ground' pressure limits (taking into account any losses at forward flight).

To determine the pressure limits specified in the system ATP development activity was undertaken with Flowmaster. Flowmaster predictions were validated against testing of actual avionics cabinets to ensure that ATP limits are set not only to ensure adequate cooling but also to highlight potential inconsistencies in cabinet build standard, such as incorrect throttling, poor sealing etc.

### LRU Calibration Testing

Historically, a disparity between aircraft test results and rig test results was evident. This would often lead to significant re-working of the system post aircraft build. The most significant factor in this was that the pressure loss against airflow characteristic of the actual LRU was different to that specified in the equipment ICD. This would lead to imbalances in the system. As a result it is now common practice to calibrate each individual LRU and mounting tray for an actual pressure loss against airflow characteristic. This along with Flowmaster allows for accurate modelling of the system.

### Conclusion

Environmental Control Systems are generally high flow low pressure systems. Performance of these systems can be significantly influenced by varying external pressure coefficients that form around the aircraft across the aircraft flight envelope. In the past, where the effect of external pressure coefficients was uncertain and difficult to accurately define, aircraft testing had demonstrated that these external pressure coefficients had an adverse effect on environmental control systems, in particular the EH101 avionics cooling system. The use of Computational Fluid Dynamics, fluid flow simulation packages and analytical models to accurately predict system performance and de-risk potential design issues has resulted in drastically reducing the amount of post design activities and rig and aircraft testing required.

## APPENDIX A – AIRCRAFT TEST RESULTS

The following section summarises test results of ACS testing performed on the EH101 CSH and the EH101 Merlin Mk3.

### Table 1. EH101 CSH ACS Test Results

| Force Cooled LRU | Requirement (l/min) @ +40°C OAT | | Achieved Flow (l/min): Original Performance | | | Achieved Flow (l/min): Performance following exercise to seal cabinets | | |
|---|---|---|---|---|---|---|---|---|
| | Bypass Open (+50°C LRU Inlet Temp.) | Bypass Closed (+45°C LRU Inlet Temp.) | Ground Run (Bypass closed) | 150 KIAS (Bypass closed) | 150 KIAS (Bypass OPEN) | Ground Run (Bypass closed) | 150 KIAS (Bypass closed) | 150 KIAS (Bypass open) |
| **Port Cabinet** | | | | | | | | |
| FCC 1 | 400 | 394 | 455 | 198 | 361 | 528 | 244 | 422 |
| ASMC 1 | 565 | 556 | 615 | 274 | 496 | 767 | 381 | 623 |
| ASMC 2 | 565 | 556 | 615 | 274 | 496 | 767 | 381 | 623 |
| HF Rx/Tx | 703 | 634 | 1217 | 551 | 980 | 943 | 478 | 759 |
| SGU 1 | 436 | 430 | 463 | 208 | 372 | 542 | 243 | 424 |
| SGU 2 | 436 | 430 | 463 | 208 | 372 | 542 | 243 | 424 |
| SGU 3 | 436 | 430 | 463 | 208 | 372 | 542 | 243 | 424 |
| Total | 3541 | 3430 | 4293 | 1918 | 3449 | 4631 | 2213 | 3699 |
| **Starboard Cabinet** | | | | | | | | |
| FCC 2 | 400 | 394 | 387 | 132 | 279 | 630 | 198 | 437 |
| Total | 400 | 394 | 387 | 132 | 279 | 630 | 198 | 437 |

### Table 2. EH101 Merlin Mk 3 ACS Test Results (continued on next page)

| Force Cooled LRU | Requirement (l/min) @ +45°C OAT | Requirement (l/min) @ +50°C OAT | Achieved Flow (l/min): Original Performance | | | Achieved Flow (l/min): Performance following exercise to seal cabinets | | |
|---|---|---|---|---|---|---|---|---|
| | Bypass Open (+55°C LRU Inlet Temp.) | Bypass Closed (+55°C LRU Inlet Temp.) | Ground Run (Bypass closed) | 150 KIAS (Bypass closed) | 150 KIAS (Bypass open) | Ground Run (Bypass closed) | 150 KIAS (Bypass closed) | 150 KIAS (Bypass open) |
| **Port Cabinet** | | | | | | | | |
| HF Rx/Tx | 1470 | 1470 | 1061 | 602 | 855 | 1384 | 724 | 1027 |
| Total | 1470 | 1470 | 1061 | 602 | 855 | 1384 | 724 | 1027 |
| **Starboard Cabinet** | | | | | | | | |
| FCC 2 | 406 | 406 | 369 | 190 | 274 | 376 | 204 | 255 |
| SIU 1 | 363 | 363 | 315 | 173 | 241 | 335 | 189 | 233 |
| SIU 2 | 363 | 363 | 315 | 173 | 241 | 341 | 194 | 239 |
| AMC 1 | 818 | 818 | 697 | 371 | 537 | 725 | 376 | 509 |
| SGU 1 | 443 | 443 | 388 | 196 | 293 | 407 | 201 | 278 |
| AMC 2 | 818 | 818 | 697 | 371 | 537 | 725 | 376 | 509 |
| FCC 1 | 406 | 406 | 493 | 256 | 363 | 471 | 230 | 320 |
| SGU 2 | 443 | 443 | 436 | 223 | 319 | 477 | 227 | 320 |
| SGU 3 | 443 | 443 | 436 | 223 | 319 | 477 | 227 | 320 |
| Total | 4503 | 4503 | 4146 | 2176 | 3124 | 4334 | 2224 | 2983 |

* DMDS OSMP introduced into the system in line with the upgraded fans

## Table 2. EH101 Merlin Mk 3 ACS Test Results (continued from previous page)

| Force Cooled LRU | Requirement (l/min) | | Achieved Flow (l/min) | | | | |
|---|---|---|---|---|---|---|---|
| | @ +45°C OAT | @ +50°C OAT | Final Cowl | | | Final Cowl with upgraded fans | |
| | Bypass Open (+55°C LRU Inlet Temp.) | Bypass Closed (+55°C LRU Inlet Temp.) | Ground Run (Bypass closed) | 150 KIAS (Bypass closed) | 150 KIAS (Bypass open) | Ground Run (Bypass closed) | 150 KIAS (Bypass closed) |
| **Port Cabinet** | | | | | | | |
| DMDS[1] | 843 | 843 | - | - | - | 1307 | 1016 |
| HF Rx/Tx | 1470 | 1470 | 1661 | 1619 | 1674 | 1720 | 1538 |
| Total | 2313[2] | 2313[2] | 1661 | 1619 | 1674 | 1720 | 1538 |
| **Starboard Cabinet** | | | | | | | |
| FCC 2 | 406 | 406 | 405 | 345 | 381 | 508 | 434 |
| SIU 1 | 363 | 363 | 359 | 309 | 339 | 444 | 383 |
| SIU 2 | 363 | 363 | 365 | 315 | 346 | 451 | 389 |
| AMC 1 | 818 | 818 | 802 | 690 | 759 | 1002 | 874 |
| SGU 1 | 443 | 443 | 453 | 385 | 427 | 576 | 497 |
| AMC 2 | 818 | 818 | 802 | 690 | 759 | 1002 | 874 |
| FCC 1 | 406 | 406 | 473 | 410 | 451 | 645 | 577 |
| SGU 2 | 443 | 443 | 479 | 413 | 456 | 660 | 589 |
| SGU 3 | 443 | 443 | 479 | 413 | 456 | 660 | 589 |
| Total | 4503 | 4503 | 4617 | 3970 | 4374 | 5948 | 5206 |

[1] DMDS introduced into the system in line with the upgraded fans
[2] Total includes DMDS