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Aircraft air conditioning heat exchangers and atmospheric fouling

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Abstract

This paper describes how the aircraft's air-conditioning system functions, such as those on the A320 including the components within the system. The need for an air-conditioning system requirement is explained, including the use of external air flow from outside to act as a cooling source (known in technical aviation terms as "ram" air). The A320 electronic controls are included in addition to the flight deck selections under normal operations and when the needs for higher levels of ventilation are required. The published literature identified indicates that the fouling and environmental pollution can affect the aircraft Environmental Control Systems is very limited, as there are few published or known materials about the particulate matter fouling / deposited on aircraft systems.

Fouling collected from large commercial aircraft is analysed using different techniques to identify the potential source emission and composition. This paper addresses the failures of the ECS due to fouling, identifies the potential sources of fouling and operational measures that may effect this safety critical systems operation.

Keywords:

Aircraft, Heat Exchangers, Fouling, Lubrication Oil Contamination, Environmental Control System

Note: Aircraft altitudes are quoted both in feet and meters to ensure SI compliance.

1 Introduction

The air-conditioning systems (Environmental Control System – ECS) that are fitted to modern large commercial aircraft are units that allow both the provision of cold and warm air on both the ground and whilst the aircraft is in-flight. The ECS bleeds hot 'clean' air from the high pressure customer manifold (high temperature, high pressure) on the gas turbine engine, which is ducted to the air conditioning pack. The pack can provide cool air to the aircraft by a simple mechanical device, namely compressing the air and passing it through wavy fin Plate Fin Heat

Exchangers (PFHE) before expanding the flow in a turbine prior to distribution. To achieve a colder output from the flow, the flow to the pack is increased (via a pack flow control valve). Warm provision is accomplished either by bypassing the flow around some of the pack components or by mixing hot air bleed with the pack outlet flow to achieve a higher outlet temperature.

All commercial aircraft require varying levels of maintenance, to ensure systems remain operational, and to enhance the safety of critical systems. Typically, the air-conditioning systems are only removed from a commercial aircraft about every 18 months, when the aircraft is scheduled for a 6 week deep maintenance action (known as a ‘C’ check). Once the air-conditioning system (the packs) has been fully removed from the aircraft, they are usually sent to a separate maintenance organisation for a full strip down of every individual component, and the primary and main PFHE are thoroughly cleaned of any fouling and deposits. However, a UK aircraft operator has found that the A320 packs are failing at a time interval between 3 to 9 months, and this is directly attributed to a fouling build up on the pack PFHE. The only method to rectify a ‘failed’ pack is to remove the entire pack from the aircraft and send the unit to the overhaul organisation for a thorough clean. Such failures are very costly in terms of the time taken to change the packs, the cost of technical delays and the additional cost of leasing additional replacement equipment.

A typical operational scenario on an A320 in commercial service includes a plausible flight schedule throughout a working day, to define how the systems are used and the total time utilised per day that illustrates how commercial aircraft perform in a typical 24 hour period. The legal requirements for cabin ventilation levels are included in the content, as is the operation of a single class high density passenger configuration, which has resulted in frequent failures of the air-conditioning system.

Sources of Particulate Matter (PM) fouling are identified from the airfield, aircraft and general operation of aircraft at an airfield. Gas turbine start sequences explain why the lubrication oil is burnt and thus resulting in ‘smoky’ engine starts. PM levels at airfields such as the London Heathrow Airport are considered, as this is where the test equipment is located, as the fouling is diluted with ambient air as distances are increased. The formation of aircraft queues are considered in ground operations and the general effect on the "ram" air that cools the aircraft packs.

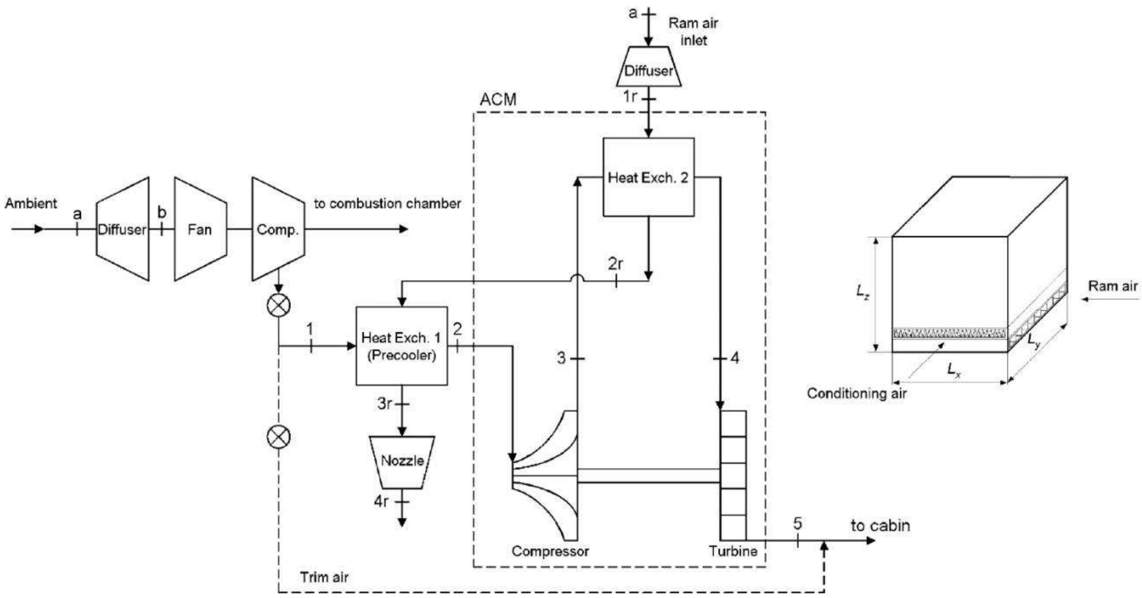

Figure 1: Typical environmental control system of an aircraft and detailed view of cross flow heat exchanger (Leo and Perez-Grande 2002).

The optimisation of an aircraft environmental control system (ECS) (where the pack is a component within the ECS) was undertaken by Leo and Perez-Grande (2002), and subsequently revised to provide a more substantiated view (2005), considering the thermodynamic and economic operation of an ECS (Figure 1). The ECS of an aircraft was treated by Leo and Perez-Grande (2005) to be considered as a single component (a black box unit), and the cost per unit of energy of the conditioning stream entering the passenger cabin was considered for a range of aircraft engine bleed pressure values. A minimum cost was suggested for a given pressure, which was close to the nominal bleed pressure. The thermodynamic and economic data discussed were values obtained from live operations, substantiated by the authors from in-service equipment. The model Leo and Perez-Grande (2005) proposed suggested that the operating costs were due primarily to the fact that the ECS has a given mass, and therefore an associated weight fuel burn when fitted to commercial passenger aircraft. The model is useful in the justification of a compact and weight reduced pack system, yet the reliability or failure events were not included in Leo and Perez-Grande's discussion, nor were references to fouling that are known to cause pack failures. The inclusion of the review of optimisation of ECS for commercial aircraft indicates that the model is heavily dependent on the physical characteristics of the unit, and does not take into consideration reliability and failure issues (including the cumulative effects of fouling).

Finally, the combination of an intense commercial operation, the ECS being a safety critical 'life support' system and the cumulative effects of fouling material on such systems illustrate the challenges faced by aircraft operators.

2 Air-conditioning systems and commercial aviation

Commercial aircraft are designed to operate worldwide in a variety of different environments. The common objective of aircraft designers when producing an aircraft is that the aircraft cabin environment should be capable of replicating 'comfortable' environmental conditions when the aircraft is 'in-service'. The term 'in-service' implies from the time the passengers embark into the aircraft, the period when the aircraft is taxiing for takeoff, the takeoff, cruise, descent phases of the flight, the landing and finally the final taxiing and disembarkation of passengers at the destination airfield. A comfortable passenger cabin typically is maintained at a temperature of 20°C (measured usually within the ECS cabin distribution system), with a local equivalent 'cabin altitude' of no more than 2,133 m (7,000 ft).

The physical environment from the origin airfield, via the flight phases to the arrival airfield changes significantly in terms of the temperature and local air pressure. In addition, the local conditions of the airfields at the departure and arrival points are likely to have different local environmental conditions, e.g. a flight departing from London Heathrow destined for Kuwait will have significantly different environmental conditions at the two airfields. For example, the local temperate conditions for London Heathrow are likely to require the cabin to be heated during the taxing phase within the UK if the outside air temperature on the ground is 10°C or below. After takeoff, the outside air temperature decreases with altitude (lapse rate) until the aircraft reaches the tropopause layer (c. 11,300 m or 37,000 ft) where the temperature at this altitude and above (6,096 m or 20,000 ft) usually remains at a constant -56°C. The extreme cold conditions of the flight require significant levels of heating to be provided to the aircraft passenger cabin, to maintain the designers required level of 'comfort.'

At the arrival airfield in Kuwait, the local conditions in summer are considerably hotter than London Heathrow, with the outside air temperatures typically reaching 50°C during the day. As the aircraft approaches the destination airfield and subsequently lands, the aircraft still needs to maintain the cabin environment of 20°C. Whilst many airfields in hot climates do have the provision of ground air-conditioning equipment, it is worth noting that this service is only available for aircraft that are parked. Such equipment is useful for cooling the aircraft cabin prior to embarkation, but from the corresponding author's personal experience in Hong Kong airport, once the external cooling is removed during the summer when the aircraft is in direct sunlight, the measured cabin temperature reaches 40°C in less than 30 minutes. Cooling is not solely a provision for passenger comfort, but more importantly, the air-conditioning system provides a cooling flow to the aircraft's electronics and electrical rack mounted equipment. If the cooling air function is removed to the electronics and electrical bay, it is possible that the electronic systems will overheat and fail. An operational consideration is that the aircraft typically closes the doors and begins ground manoeuvres some 30 minutes before the allocated take off time, thus the need for the provision of cooling air to the aircraft.

The heating and cooling functions are required for a safe, comfortable passenger cabin environment on both the ground and inflight, which are provided from the mechanical systems fitted within the aircraft structure. Older aircraft (pre-1960's) used a Freon type refrigerant rig to provide the cooling function for the cabin air, but the weight, cost and poor reliability of the product made them obsolete in large commercial aviation (aircraft with a maximum takeoff mass greater than 5700 kg) post 1970's. Due to space and weight limitations that are unique to commercial aviation, a novel system component was fitted to aircraft to utilise the engines bleed air (high pressure and high temperature), to the device known as an air conditioning 'bootstrap' pack. The term pack is used to describe all the mechanical components associated with the air conditioning system that are fitted to the aircraft. An aircraft pack is a mechanical device that uses a compressor and a turbine coupled with plate fin heat exchangers (PFHE's) to control the outlet air temperature (and flow) to the cabin.

Hot compressed clean air is taken from the gas turbine engines, and is known as the 'bleed air.' The bleed air is ducted from the high pressure compressors at a manifold, known as the 'customer bleed' port. This hot air is metered through a bleed air valve, and is required for commercial aviation to pressurise the passenger cabin, and to provide heating and fresh air for ventilation purposes. The bleed air is too hot and too high pressure to directly duct into the aircraft cabin, as typically temperatures of the air are about 200°C and pressures can exceed 1 MPa at the customer bleed manifold. Hot bleed air from the engine compressors is metered through the bleed air valve (located in the engine pylon) on to the ECS pack: inside the pack unit, the air is further metered through a pack flow control valve (Figure 2), passed through a primary heat exchanger (where there is a temperature reduction), then to an 'air cycle machine bootstrap turbo machinery' comprising the Compressor (C) and the Turbine (T). The bootstrap Compressor (C) centrifugally compresses the bleed air and thus raises the temperature and pressure, and the air is passed to a secondary heat exchanger (where there is a temperature reduction in the air). The air flows to a water extractor, which is required, since ice crystals can form in the bootstrap which if not removed would cause significant damage to the Turbine (T) and associated turbo machinery. The air passes out of the turbine with an associated drop in temperature and pressure as the outlet bleed air expands rapidly. Finally, cool 'conditioned' air is distributed into the cabin air system (Figure 2).

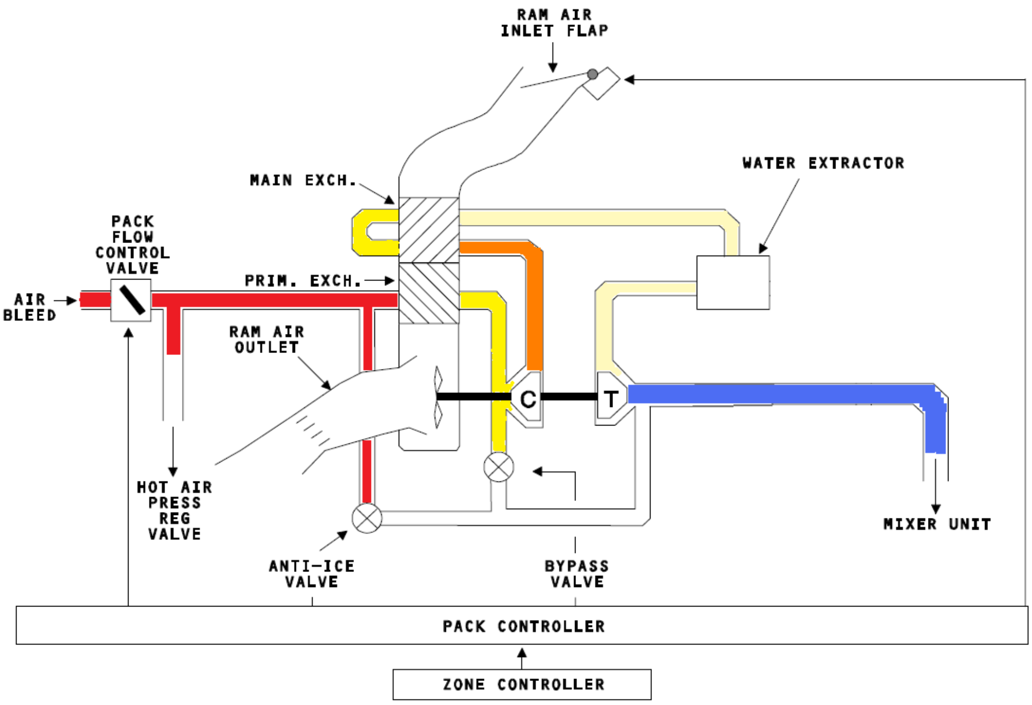

Figure 2: Schematic of the A320 air conditioning bootstrap pack when the aircraft is on the ground (Airbus 1992).

Ambient air (also known as “ram” air) provides the cooling in both the primary and secondary exchangers. The “ram” air flows are controlled by the electronic pack controller by opening and closing the “ram” air inlet flap, and opening or closing mechanically louvered vents at the “ram” air outlet. When the aircraft is operating on the ground, that is whilst it is taxiing, the “ram” air flows are not sufficient to provide adequate cooling for the pack PFHE, even though both the “ram” air inlet flap and outlet louvers are fully open. The “ram” air flows are increased by the use of a mechanical shaft and fan which is coupled to the compressor/ turbine shaft (Figure 2). As the bleed air is fed to the pack, the flow causes the compressor to rotate, the mechanically powered fan induces a “ram” air flow. The greater the bleed air supply, the faster the bootstrap turbo machinery and likewise, the greater the “ram” air cooling flow.

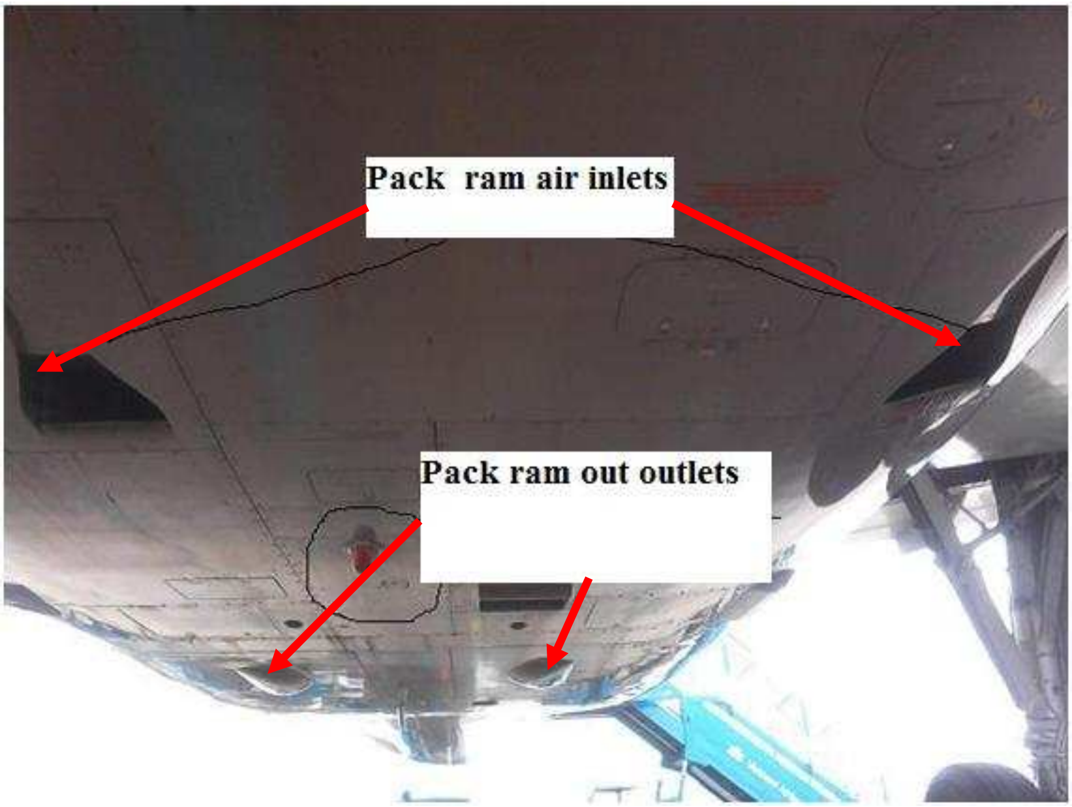

Figure 3: Photograph of the Airbus A320 on the ground, with the pack “ram” air inlets (fully open) and exhaust outlets, viewed from underneath the aircraft (facing aft).

The “ram” air inlets are positioned below the water line of the aircraft, on the underside of the fuselage located slightly aft of the wing root leading edge (Figure 3). When the aircraft is on the ground, the pack controller fully opens the “ram” air inlet flap to permit a maximum external cooling “ram” air flow to the pack PFHE.

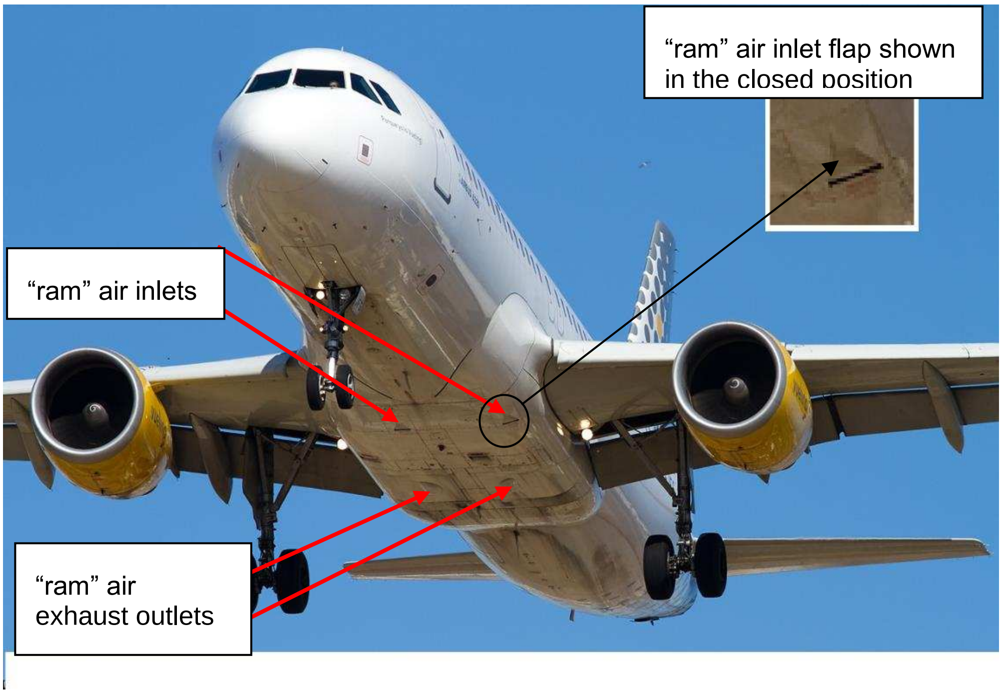

Figure 4: Photograph of the Airbus A320 taking off, with the indicated pack “ram” air inlets and outlets, including an enlarged inset of the “ram” inlet in the closed position.

Conversely, when the pack controller determines that full “ram” air cooling is not required, the “ram” air inlet flap is mechanically closed (Figure. 4). When the aircraft is in flight, there is less need for providing significant quantities of cold fresh air to the cabin, and due to the cold external conditions as the altitude increases, warm air is required to heat the passenger cabin to provide a comfortable cabin environment.

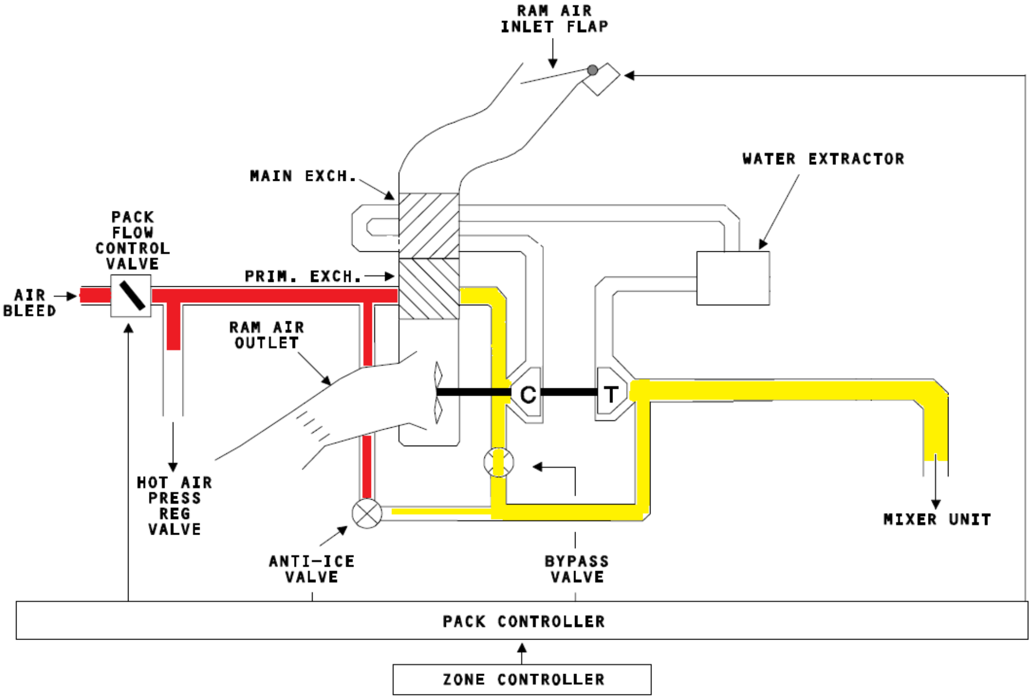

Figure 5: Schematic of the Airbus air conditioning bootstrap pack operation when the aircraft is inflight, providing heating to the cabin (Airbus 1992).

The pack achieves the desired cabin conditions in a number of ways. Firstly, the “ram” air inlet flap is moved mechanically towards the closed position to restrict the cooling flow to the PFHE. The bleed air flow continues to pass through the primary exchanger, but by reducing the “ram” air cooling flow, the primary outlet temperature does not fall as significantly as on the ground. Additionally, the pack bypass valve (within the pack) is fully opened (Figure. 5) thus allowing the majority of the bleed air flow to bypass the bootstrap turbo machinery, thus the cabin flow is hotter than the pack configuration illustrated (Figure 2). The use of the pack controller (which is a solid state electronic control unit) allows either cold or hot air to be provided to the aircraft cabin, depending on the phase of the flight and the current physical conditions.

The aircraft bootstrap air-conditioning system has a common vulnerability, namely that of the pack overheating in service. If the flight crew select a low desired cabin temperature under ‘normal’ flow conditions (using the zone controller), and the aircraft structure is very hot from the solar gain operating in a sub-tropical environment, the pack controller attempts to achieve the required cabin temperature by increasing the bleed air flow to the pack. When high bleed air flows are ported to the pack, the turbo machinery responds and provides a cooler flow. However, this is dependent on the “ram” air cooling flow being capable of force convecting the bleed air heat to the PFHE. If the outside air temperature of the “ram” air is too high, the PFHE will be unable to cool the hot bleed air sufficiently, which causes the pack temperature to rise rapidly. The pack controller attempts to counter this effect by porting a higher bleed air flow to the turbo machinery (negative feedback effect). If the “ram” cooling and PFHE’s continue to fail to cope with the demand of the cool cabin air requirements and the heat transfer limitations, the pack can enter a thermal runaway scenario (i.e. the pack temperature exceeds about 260°C).

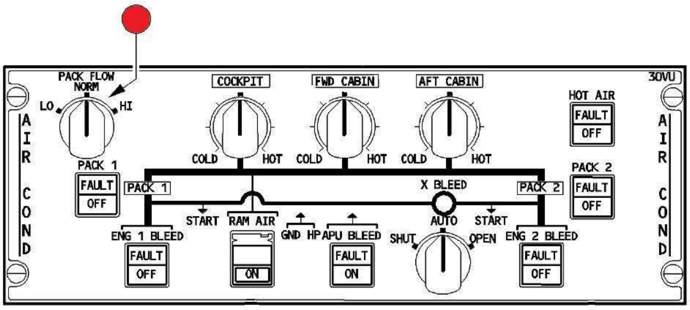

Figure 6: The A320 air conditioning over head panel, with the pack flow selector highlighted (Airbus 1992).

To prevent the pack and turbo machinery from a thermal runaway situation, a number of critically placed thermocouples are situated within the pack, which gives a warning signal to the flight crew via the flight deck indication system. If a thermal runaway situation is allowed to progress, the turbo machinery will rotate at such a rate that it will generate sufficient heat (from friction) to cause the turbo machinery to seize, or even worse, the pack components within the pack to combust. Flight crew are trained to isolate a pack that is indicating an ‘overheat’ condition by closing the pack flow valves switches on the overheat panel (Figure 6). If the aircraft is on the ground when the overheating occurrence takes place, the flight crew should return to the parking stand and seek an engineering action to rectify the fault.

The aircraft packs are usually operated with the pack flow selector (Figure 6) in the ‘norm’ position, ensuring that the correct level of ventilation of the cabin (i.e. in a standard passenger configuration, namely a business and economy class) is achieved inflight. There are two air-conditioning packs fitted to the A320 aircraft, and a similar number on other commercial aircraft. Pack 1 typically supplies the flight deck, electronic and electrical bay and the front section of the passenger compartment, whilst pack 2 serves only the mid to rear passenger compartment. The normal procedure is for the flight crew to select a slightly lower temperature for pack 1 to ensure that the flight deck and electrical systems are adequately cooled. In exceptional circumstances, such as in an emergency condition when the turbo machinery within the pack has seized inflight, it is possible for one operational pack to be operated under ‘hi’ flow conditions (Figure 6) to provide adequate ventilation to the passengers and crew prior to an unscheduled landing.

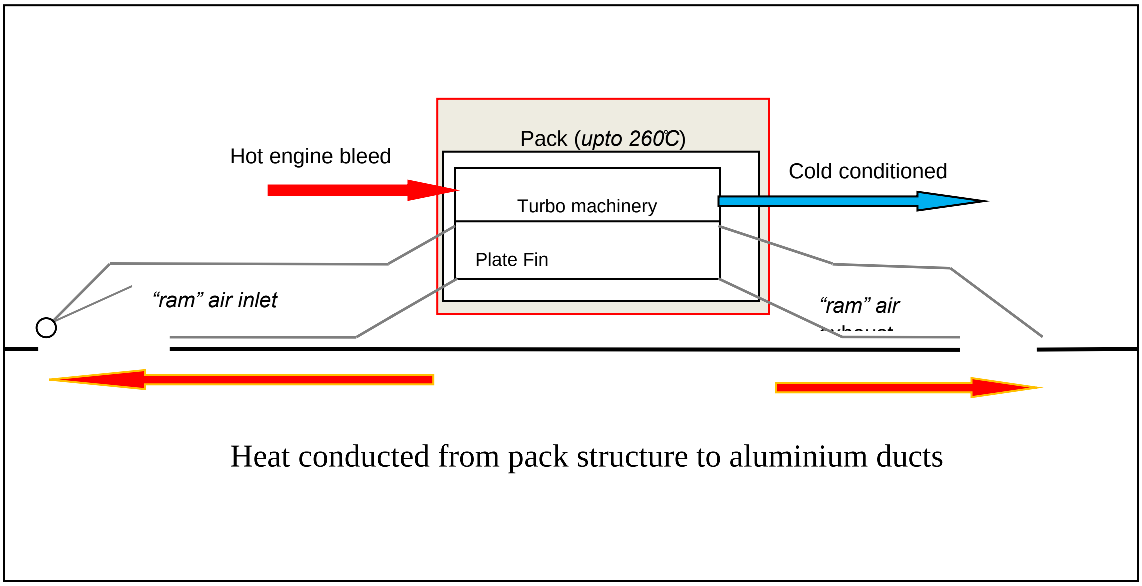

Figure 7: Diagram of the hot pack components, fitted within an aircraft that is conducting heat to the “ram” air inlet and exhaust ducts (ducts rastered in grey)(Wright 2013).

The materials used in the air conditioning pack (including the PFHE) and duct work are mostly aluminium alloys, as indicated in Figure 7, where the rastered grey lines represent the aluminium ducting. The use of aluminium alloys (as a structural material) in commercial aviation is commonplace, as the material is light, yet strong, and may be repaired with some ease. However, an additional property that aluminium demonstrates is that of a high thermal conductivity, which is a good property within the PFHE matrix, as the transfer of heat between the flows across the plates and fins is critical. As the pack is fastened directly to the “ram” air ducting, it is likely that the aluminium ducting, both forward and aft of the pack, will conduct heat, in addition to the heat transfer within the PFHE.

The conduction of heat from air-conditioning packs in other commercial aircraft has been problematic in the past. The Boeing 747 classic is an example of this, where one of the packs is located directly below the central fuel tank. When the air-conditioning pack is in high demand, the pack and the surrounding structures conduct heat away from the pack: the central fuel tank often acts as a heat sink, as fuel is typically cold if the aircraft is cold soaked. However, if the central tank is allowed to become empty, the pack conducts heat to the central tank structure, thus raising the temperature of the residual fuel. If the fuel temperature is raised sufficiently and an additional source of ignition is added (i.e. a spark from an internal wiring loom within the tank), a central tank fuel fire/ explosion may occur.

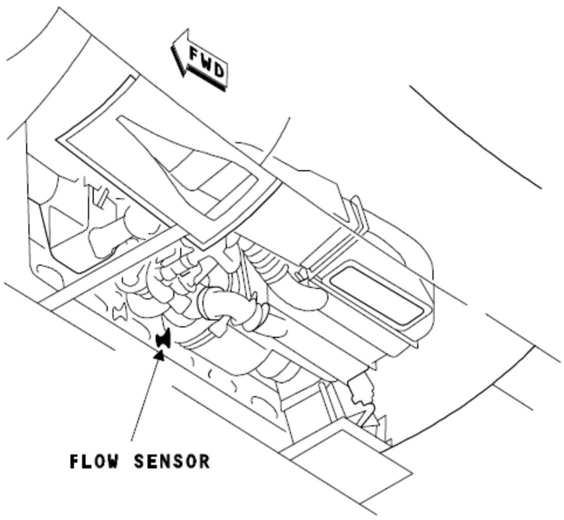

Figure 8: A320 Air-conditioning “pack” fitted within the air-conditioning bay on the underside of the aircraft (Airbus 1992).

The location of the pack (Figure 8) demonstrates the close proximity to the unit within the air-conditioning bay. Access to the pack is very limited to the pack design and the severe limitations of available space. If a maintenance action is required for the pack, the engineering action often involves disconnecting the pack from the “ram” air inlet and exhaust, disconnecting the support mountings and removing the entire pack from the underside of the aircraft structure. Due to the mass of the pack, the units are usually hoisted in and out of the air-conditioning bays.

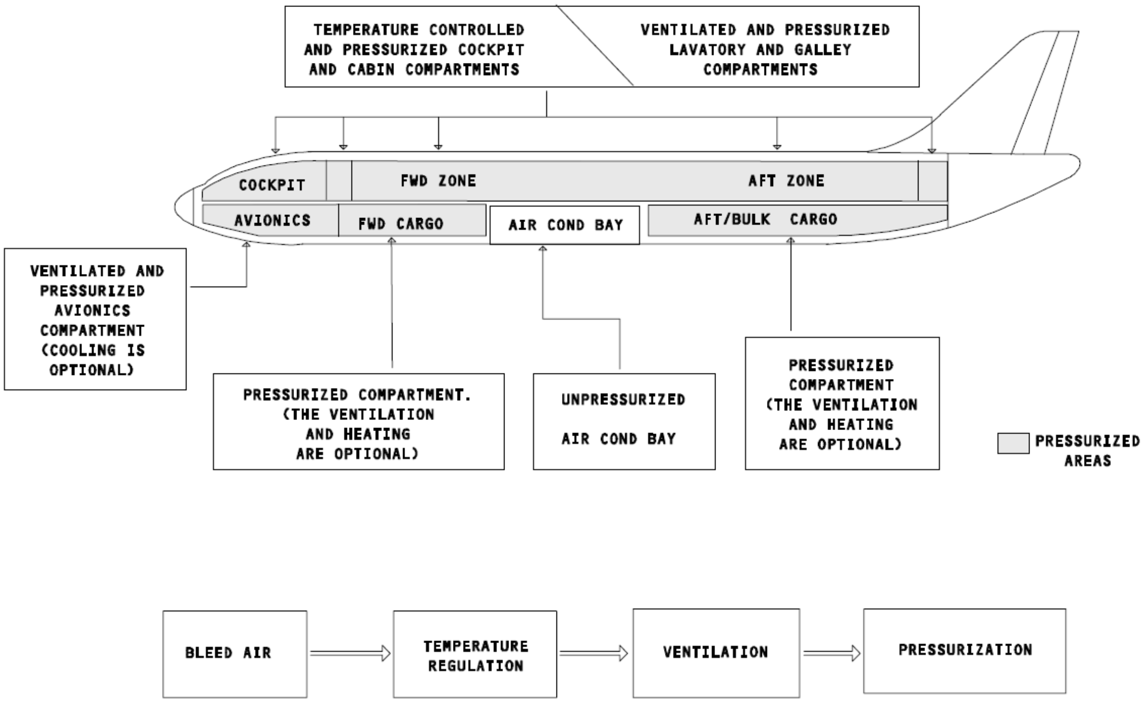

Figure 9: A schematic of the air conditioning and ventilation A320 (Airbus 1992).

A simplified schematic of the air-conditioning system within the A320 (Figure 9) shows the general location of the air conditioning bays (one for each pack) and the distribution of the conditioned air throughout the aircraft.

3 Aircraft general operation in commercial service within a 24 hour period

It is useful to consider the general operation of an A320 commercial passenger aircraft, as the general use affects the performance and the maintenance schedule of the aircraft, as the aircrafts' daily operation is likely to remain similar between the maintenance 'C' checks (i.e. the 18 month period). It is assumed that the aircraft is operated by an airline in a short to medium haul scheduled pattern, based in Northern Europe in a single 24 hour period. From the corresponding author's personal experience of being employed in commercial aviation, the A320 aircraft can be utilised to fly four sectors of approximately 2 hours flying time, for which the A320 is ideally suited.

At the start of each day (c. 0500hrs), the aircraft will be located either on a parking stand or at a gate prior to the first flight. It is likely that the aircraft is cold, having been parked outside overnight, undergoing routine maintenance from the previous evening. The aircraft is heated to a comfortable temperature by the flight crew running the auxiliary power unit (APU) to provide ground power (if needed) and compressed hot bleed air to the air-conditioning packs.

A full approximate A320 commercial utilisation in a single 24 hour period (Table 1) is based on the assumptions that the aircraft is free from major technical and non-technical delays. With the technical issues that are expected, the flying programme will permit the aircraft to operate until the destination airfields curfew, which is typically 2300 hrs. Note: All times indicated are in coordinated universal time UTC (which is the equivalent of GMT).

The total time for each day where the aircraft is operating the packs either on the ground or below 5,000 ft (based on approximated A320 use, table 1) is 4 ½ hours. This suggests that although the total daily flight time is approximately 8 hours, the pack is mechanically cooling the hot bleed air for approximately 50% of the operational flight time on the A320.

Lastly, the illustration of the daily operation expanded across an approximate 18 month period between ‘C’ checks combined with the cooling assumption, indicates that the mechanical cooling work of the pack is likely to be detrimentally affected by the cumulative effects of fouling of the ECS as the PFHE’s progressively foul.

Table 1: A typical A320 aircraft activity in a single 24 hour period (Wright 2013).

Time	**Description**	**Air-conditioning pack operation**	**Grnd**	**Flight**
	Curfew. Maintenance actions until 0600hrs			
0530 hrs	Maintenance actions until 0600hrs (Flight crew briefing)	Off	Y	
0600 hrs	Flight crew arrive at aircraft	Off	Y	
0630 hrs	Passengers boarding	On (APU on, Eng off)	Y	
0700 hrs	Doors close, push back, start taxiing	On (APU on, Eng ON)	Y	
0720 hrs	Take off run and initial climb (to 5,000 ft)	On - Engines on	Y	Y
0730 hrs	Climb and cruise	On - Engines on		Y
0800 hrs	Cruise	On - Engines on		Y
0830 hrs	Start descent, holding pattern,	On - Engines on		Y
0900 hrs	Final approach, land, taxi in, park at gate	On (APU on, Eng ON)		Y
0930 hrs	Passengers disembark, cabin preparation, crew disembark	Off	Y	
1000 hrs	Flight crew arrive at aircraft	Off	Y	
1030 hrs	Passengers boarding	Off	Y	
1100 hrs	Doors close, push back, start taxiing	On (APU on,Eng off)	Y	
1120 hrs	Take off run and initial climb (to 5,000 ft)	On (APU on, Eng ON)	Y	Y
1130hrs	Climb and cruise	On - Engines on		Y
1200 hrs	Cruise	On - Engines on		Y
1230 hrs	Start descent, holding pattern,	On - Engines on		Y
1300 hrs	Final approach, land, taxi in, park at gate	On (APU on, Eng ON)		Y
1330 hrs	Passengers disembark, cabin preparation, crew disembark	Off	Y	
1400 hrs	Flight crew arrive at aircraft	Off	Y	
1430 hrs	Passengers boarding	On (APU on, Eng off)	Y	

1500 hrs	Doors close, push back, start taxiing	On (APU on, Eng ON)	Y	
1520 hrs	Take off run and initial climb (to 5,000 ft)	On - Engines on	Y	Y
1530 hrs	Climb and cruise	On - Engines on		Y
1600 hrs	Cruise	On - Engines on		Y
1630 hrs	Start descent, holding pattern,	On - Engines on		Y
1700 hrs	Final approach, land, taxi in, park at gate	On (APU on, Eng ON)		Y
1730 hrs	Passengers disembark, cabin preparation, crew disembark	Off	Y	
1800 hrs	Flight crew arrive at aircraft	Off	Y	
1830 hrs	Passengers boarding	On (APU on, Eng off)	Y	
1900 hrs	Doors close, push back, start taxiing	On (APU on, Eng ON)	Y	
1920 hrs	Take off run and initial climb (to 5,000 ft)	On - Engines on	Y	Y
1930 hrs	Climb and cruise	On - Engines on		Y
2000 hrs	Cruise	On - Engines on		Y
2030 hrs	Start descent, holding pattern, final approach	On - Engines on		Y
2100 hrs	Final approach, land, taxi in, park at gate	On (APU on, Eng ON)		Y
2130 hrs	Passengers disembark, cabin preparation, crew disembark	Off	Y	
2200 hrs	Maintenance actions until 0600hrs	Off	Y	

4 Legal fresh air cabin requirements, high density seating aircraft operations and pack failure on the ground

Upto 1996, the Federal Aviation Administration (FAA, USA) and the Joint Aviation Authority (JAA, Europe) had the same basic requirement for cabin ventilation rates. These regulators required a minimum supply of 10 cubic feet per minute (cfm) of fresh air per flight crew member, which "must be free from harmful or hazardous concentrations of gases or vapours" (Federal Aviation Administration 1965), which is mixed with the returned cabin air in the ventilation system.

The normal capacity of the A320 is 150 passengers in a two class configuration, yet a single configuration can provide seating for up to 180 economy passengers (Airbus 2001). The resulting high flow operation causes the air conditioning system to operate at 120% of the normal manufacturers flow. The ‘Hi’ flow operation at levels greater than the normal operation may be required to provide additional levels of ventilation during abnormal situations/ operations. One such abnormal operation would be smoke in the passenger cabin, where additional fresh air is required to prevent asphyxiation.

In a single cabin configuration of full economy seating (180 passengers), to meet the legal requirements regarding fresh air provision, the flight crew operate the packs on ‘Hi’ flow (Figure 6). A UK based airline has reported to the author that a much higher than expected air-conditioning system failures (pack overheat) are observed in their A320 fleet, caused by overheating whilst the aircraft is either on the ground or during the take-off / landing phase of the flight. During these specific operations, the “ram” air does not appear to be sufficient to provide sufficient cooling to the primary and secondary PFHE, even though the “ram” air inlet flap is fully open.

The overheating in the pack has been directly attributed to particulate matter fouling and accretion in the air conditioning pack PFHE matrix, which was confirmed by the air-conditioning overhaul specialist organisation once a pack was removed and sent away for repair. When excessive levels of particulates are deposited into the PFHE matrix, the individual passage hydraulic diameter reduces as the fouling adheres to the inside of the unit. Assuming the flow remains the same, the reduction of the porosity will result in an increase of the differential pressure across the plate fin heat exchanger (PFHE). Thus, the thermal performance of the fouled heat exchanger decreases, to the extent that the pack reaches higher than acceptable operational temperatures and this would usually result in the flight crew “shutting down” the overheating pack when the pack temperature exceeds 260°C. The implications linking the increase in differential pressures with the effects on heat transfer will be discussed separately. Rectification of this pack overheating system failure can only be achieved by removing the pack from the aircraft, returning the pack unit back to the original equipment manufacturer (OEM) for analysis and deep cleaning of the pack to remove the fouling contaminants from the PFHE components.

5 Sources of airborne pollutants that may foul and deposit in the PFHE

The UK Department for Transport (DoT 2003) white paper discusses air transportation development over the next 30 years**.** The paper and content is of specific importance to academic study, as it is anticipated that increased levels of growth of commercial aviation will lead to higher levels of airborne debris at or near to an airfield, thus potentially effecting the operation of aircraft heat exchangers. The numbers of aircraft operating at a given period of time will not be correlated to the levels of technical dispatch reliability, but it would be expected that increased levels of operation will lead to higher rates of failure of the air-conditioning systems directly attributed to pack PFHE fouling.

The effects of tyre smoke from landing aircraft (Bennett 2009) was considered as sources of airfield pollution. Bennett was able to take samples of particulate matter from Airbus and Boeing aircraft landing gears main legs, and conduct analyses. The material gathered from Bennett's research noted that there was as no distinction between tyre smoke or braking activities. It was found that the samples had three distinctive peaks in distribution: 2 µm, 10 µm and 50 µm. The smaller particulates of a mean diameter of 1-2 µm were considered to be fragments of larger soot agglomerations.

Energy dispersive X-ray spectroscopic (EDS) analysis of pack PFHE fouling samples taken from large commercial aircraft confirmed elemental presence of Al, Ca, C, Co, Cr, Cu, Fe, K, Mg, Na, Ni, O, P, S, Ti, V and Zn elemental content (Wright, 2013). Some of the elements are attributed to airfield asphalt concrete (Al, Ca, Fe, Na, O, S) wear and tyre (C, S, Zn) composition.

Bennett conducted light detection and ranging (LIDAR) analysis on the emissions from an operational BAe 146, which was specifically commissioned to provide the experimental pollutants at Cranfield Airport. The LIDAR equipment that was operated measured a sampling volume of approximately 500 l. Bennett found that the bulk of the visible aerosol in tyre smoke was too coarse to be considered respirable (i.e. in the ultra-fine region, < 1 µm), yet the peaks indicating the emission sizes ranged between 10 to 50 µm. Further, Bennett's research also noted that in addition to tyre wear, airfield runway wear produced large quantities of mechanically produced dust from the runway surface.

5.1 Particulate Matter (PM_{10})

The Department for the Environment, Food and Rural Affairs UK (DEFRA) defined (in 2005) particulate matter being:

> *"classified according to its size and this classification is used in concentration* measurements. For example, PM_{10} is – to a good approximation – the concentration of *particles that are approximately equal to 10 µm."* (DEFRA 2005).

Airborne particulate matter is made up of a collection of solid and/or liquid materials of various sizes that range from a few nanometres in diameter (about the size of a virus) to around 100 µm (about the thickness of a human hair). It consists of both primary components, which are released directly from the source into the atmosphere, and secondary components, which are formed in the atmosphere by chemical reactions. Further, particulate matter comes from both human made and natural sources. PM contains a range of chemical compounds and the identity of these compounds is dependent on the source materials (see Table 2).

Such PM, dispersions and other environmental fates may be ingested into the ECS (including small quantities of water droplets suspended in air), but the general location of the ECS inlet can be assumed that ingress of foreign bodies (including possible nose gear water spray) is minimised (see Figure 3).

Particulate matter is known to foul PFHE, resulting in changes in heat transfer performance, thus an understanding of particulate matter and levels of concentration are of interest to the study. A second publication "Project for sustainable development at London Heathrow" Department of Transport, (DoT 2004) introduces government recorded data making reference to dispersion modelling close to airfields and the types of measured emissions found close to the airfield (London Heathrow). London Heathrow International Airport, located in West London, is adjacent to the M25 motorway. Pollutants monitored included concentrations of NO_2 (gas) and particulate matter (including PM_{10}). The Particulate Matter is described as one of the main particulate contributions to airborne fouling, and therefore particular attention will be given in this review to its particle size, distribution, source and effect. $PM_{\mathbf{10}}$ is specifically named in this publication as the main size classification of particulate matter.

Table 2.2: Sources of particulate matter (DoT 2004).

Primary components	Sources
Sodium chloride	Sea salt.
Elemental carbon	Black carbon (soot) is formed during high temperature combustion of fossil fuels such as coal, natural gas and oil (diesel and petrol) and biomass fuels such as wood chips.
Trace metals	These metals are present at very low concentrationsand include lead, cadmium, nickel, chromium, zinc and manganese. They are generated by metallurgical processes, such as steel making, or by impurities found in or additives mixed into fuels used by industry. Metals in particles are also derived from mechanical abrasion processes, e.g. during vehicle motion and break and tyre wear.
Mineral components	These minerals are found in coarse dusts from quarrying, construction and demolition work and from wind-driven dusts. They include aluminium, silicon, iron and calcium.
Secondary components	**Sources**
Sulphate	Formed by the oxidation of sulphur dioxide (SO_2) in the atmosphere to form sulphuric acid, which can react with ammonia (NH_3) to give ammonium sulphate.
Nitrate	Formed by the oxidation of nitrogen oxides (NO_x – which consists of nitric oxide (nitrogen monoxide, NO) and nitrogen dioxide (NO_2) in the atmosphere to form nitric acid, which can react with NH_3 to give ammonium nitrate. Also present as sodium nitrate.
Water	Some components of the aerosol form of particulate matter, such as ammonium sulphates and ammonium nitrates, take up water from the atmosphere.
Primary and secondary components	**Sources**
Organic carbon	Primary organic carbon comes rom traffic or industrial combustion sources. Secondary organic carbon comes from the oxidation of volatile organic compounds (VOCs). There may be several hundred individual components. Some of these trace organic compounds, such as certain polycyclic aromatic hydrocarbons, are highly toxic.

One such reason for the emphasis of PM_{10} relates to the monitoring capability and legislation requirements of local authorities to monitor particulate matter, as this size specification is the size range legally mandated for Europe wide monitoring.

The inclusion of particulate matter is of specific interest to this research, since it is believed that such materials are likely to accrue on heat exchanger surfaces with the potential to affect the heat transfer ability. The Department of Transport paper does not include details of future pollutant models or contents that would enable one to calculate/ generate the emissions that would be required should this task be required. The methodology used by the government selected 'panel members' (individuals selected by Department for Transport) provided written details of recommendations on how to set up detailed 'Bottom up inventory' of pollutant sources. This approach was considered too qualitative/ subjective, and therefore considered to be limited for this paper.

Measurements of the concentration of particulate matter in the air are made by recording the mass of particulate matter in one cubic metre of air, using the units micrograms per cubic metre, $\mu g\ m^{-3}$ (Quincy et al. 2009). The mean UK limit for particulate matter PM_{10} is 40 $\mu g\ m^{-3}$, across the UK as a whole (DoT 2004): The Department for Transport Report stated that the maximum value measured were 7.3 $\mu g\ m^{-3}$ with an estimated mean average around the London Heathrow vicinity of 24-25 $\mu g\ m^{-3}$. Measurements of smaller particles namely $PM_{2.5}$ were estimated to be between 17-21 $\mu g\ m^{-3}$.

This report (DoT 2004) cites the sources of PM_{10} pollution include:

- Aircraft from both ground and flight operations, including operation of Auxiliary *Power Units (APU's), operations of tyres and brakes and ground engine* tests.
- Airside vehicles - both supportive and service vehicles e.g. aircraft start up equipment, ground power units.
- Road vehicles, at both landside and airside. (Airside is within the security perimeter of the airfield, and landside is all other areas not subject to strict security controls).
- Airport car parks, bus stations and taxi queues.
- Airport building heating, ventilation and air conditioning (HVAC) systems including boiler plant.
- Airport fire training exercises.

Additional emitted sources of emissions are discussed, including the critical phases of flight, namely take off and landing, yet the quantified values pertaining to the emission types are not contained in this document (DoT 2004).Whilst an understanding of PM fouling is important to this research, the operation of aircraft close to fouling sources needs to be carefully considered. A general commercial aircraft on an approach pattern is suggested in accordance with the International Civil Aviation Operation (ICAO) documentation. The approach begins when the aircraft is at an altitude of 1,524 m (5,000 ft) and at a distance of 10 nautical miles (20 km) from the threshold (the landing point of the runway) and the aircraft will be approximately at a height of 914 m (3000 ft). At this time, an initial landing flap setting is likely to be made and this results in a deceleration of the aircraft. At approximately 6.5 nautical miles (13 km) the undercarriage of the aircraft is extended and the aircraft is then approximately at a height of 609 m (2,000 ft). The final flap setting is made at 5 nautical miles (10 km) at an approximate altitude of 457 m (1,500 ft). When the aircraft is in the approach condition, typically the pack is operated in such a condition to provide cooling to the cabin and flight deck.

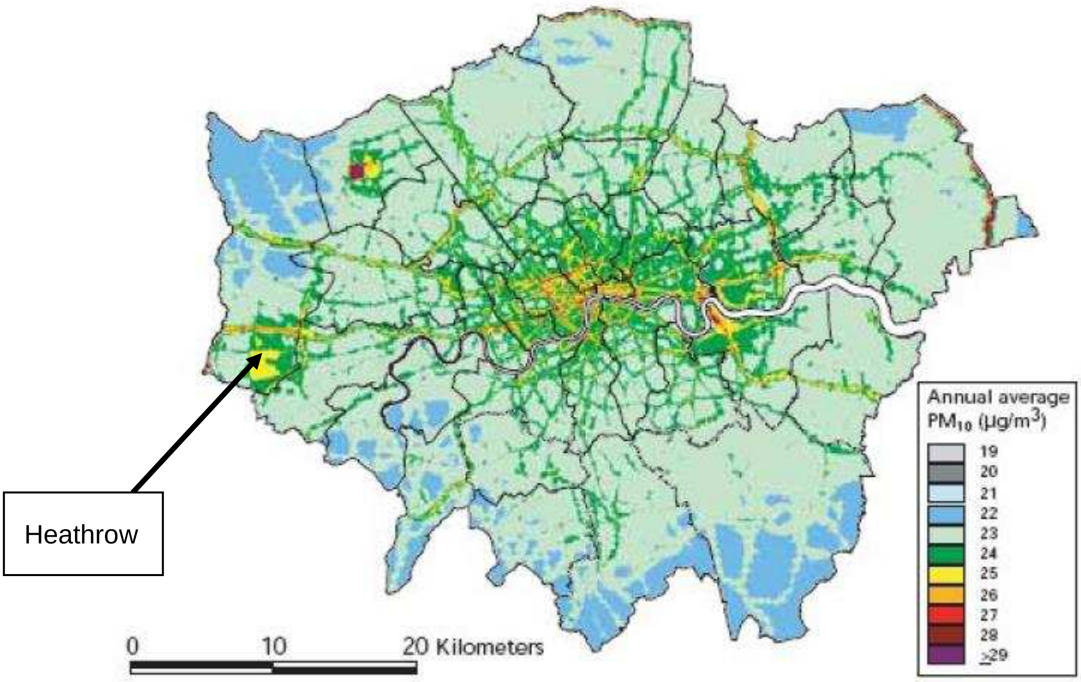

Figure 10: 2004 PM_{10} concentrations in Greater London (DfT 2004).

This account is particularly important since the operational failure of air-conditioning systems observed by commercial airlines is not in flight, but whilst the aircraft is on the ground, typically after the aircraft has flown a sector and then is performing ground operations. It is known (Airbus 2001) that the initial and final phases of flight (the approach) where the aircraft is known to fly at reduced speeds, reduces the mass airflow through the air conditioning heat exchangers, the "ram" inlet flap is in the open position and coupled with this is the ambient air containing higher values of particulate matter, namely PM_{10}. There are areas of higher than expected levels of PM_{10} in the West London region, as indicated by the brightly colour shaded regions representing high PM concentrations (Figure 10). The highest level of the pollution in West London corresponds to London Heathrow's geographical location and close proximity to busy motorways (M25, M4, M40), which displayed very high levels of PM_{10}. It should also be noted that commercial aircraft operating from Heathrow airport standard take-off and approach routes are likely to track the aircraft across central London, which is also high in PM_{10} aerosol, thus further affecting the deposit of debris on the heat exchangers (Figure 10).

Auxiliary power unit (APU) emissions from their use is significantly less complex than the emissions from aircraft. This is because the APU operation is typically whilst the aircraft is on ground without ground services: The APU may be used in early and late phases of flight namely take off and landing, but generally the use of APU in flight in not necessary (DoT 2004). A relationship for the total APU emissions is given by Equation 1 (DoT 2004):

$$APU\ emissions = \sum_{mode\ e=1}^{mode\ e=4} Time_{mode} \times Fuelflow_{mode} \times Emission\ Index_{mode} \tag{1}$$

This suggests that the type of operation for a given APU, coupled with the rate of fuel flow results in an emission index of the respective mode. The mode conditions contained within equation (1) are defined as:

(i) No load, (ii) Electric, (iii) Full ECS + electric, and (iv) Main Engine Start (MES) + electric,

The report noted that modes (ii) and (iii) emitted similar levels of NO_x and PM_{10} concentrations, whilst the modes (iv) and (i) were distinct more so in terms of the emission levels. However, the report does not include reference to particulate matter composition, or of the size distribution of the average particulate size. This is because the measurement for the particulates at present is only mandated for PM_{10} (Quincy and Butterfield 2009). The inclusion of a size distribution of particulates including analysis of the Volatile Organic Content (VOC) would be beneficial to this research. The APU emissions are higher than modern gas turbine main engines, and this suggests that the use of APU will have a significantly higher impact on the reliability of air conditioning heat exchangers than modern gas turbines due to the levels of PM_{10} produced (DoT 2004). In-flight, APU use is normally restricted to a low altitude operation (dependent on aircraft type, APU specification and airline 'local' procedures), which also suggest slower aircraft operating speeds thus lower mass airflow though the respective heat exchanger matrixes. Airside vehicle traffic contributes to PM_{10} being produced as an aerosol, but due to the lack of exact data values for vehicle distances travelled, the report is unable to give an exact breakdown of vehicle type and PM_{10} mass production. However, this will not hinder this investigation, as values of PM_{10} have been monitored at various sites both inside and outside the airport vicinity, thus trends of PM_{10} pollution are known from observations.

Lastly, the 2010 volcanic eruptions of Eyjafjallajökull, Iceland, demonstrated the potential unexpected effects that airborne ash PM pose to commercial aviation. Whilst the volcanic ash PM emissions were short lived, the operational effect on European aviation was considerable.

6. Analysis of fouling from ECS of a B747

The literature review conducted has indicated the lack of publication materials on fouling affecting commercial aviation. To remedy and to investigate this scope further, fouling was removed from the ECS PFHE of a Boeing 747-400 that was undergoing a 'heavy' maintenance 'C' check in the UK. The fouling collected was latterly analysed using Thermo-Gravimetric Analysis (TGA), electron microscopy and elemental X-ray analysis (EDS).Thermo-gravimetric analysis (TGA) was conducted on the front and rear face samples. TGA allows samples to be analysed to represent the loss of mass (of a small test sample) verses the temperature profile, measured with time. The TGA equipment has been programmed to heat samples in three consecutive heating stages, which corresponds to the equipment specification of the analytical apparatus. The rate of heating was 25ºC min^{-1}, being a calibrated pre-programmed rate of heat increase within the equipment test sample.

Stage 1: The sample is heated in a dry N_2 environment to 105ºC for 15 minutes: this encourages water evaporation.

Stage 2: The sample temperature is raised to 900ºC and continued in the N_2 environment for an additional 55 minutes. This ensures that all the volatile fractions are evaporated in a non-oxygen environment.

Stage3: The N_2 environment is replaced with a compressed air supply and a slight increase in temperature to 925ºC for a further 15 minutes. The change of environment allows the carbon content to be analysed by weight, as the carbon based materials remaining in the N_2 environment burn to produce an ash residue when compressed air is introduced into the TGA equipment.

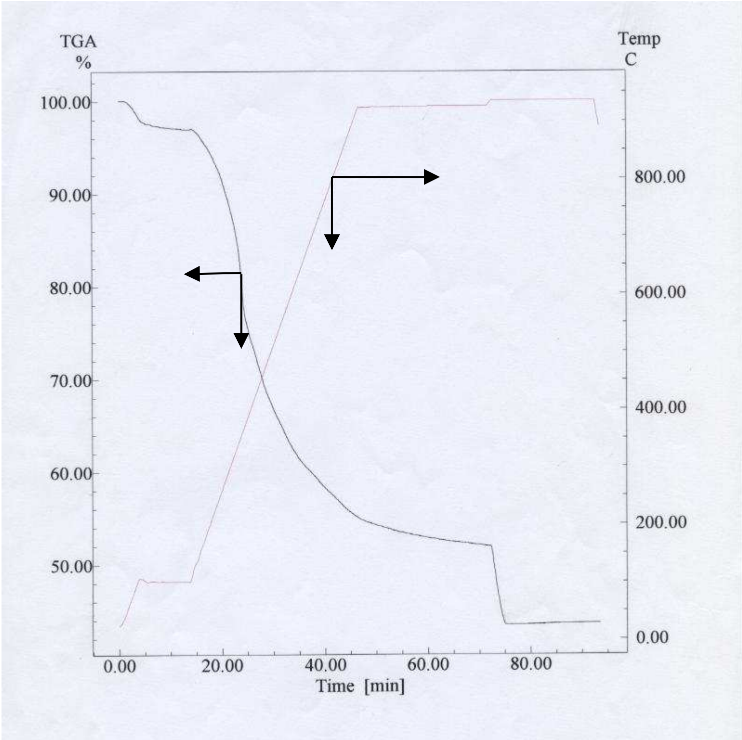

Figure 11: TGA analysis of fouling from the front face of the B747-400 heat exchanger (Wright 2013).

Description of Figure 11 (front face): Stage 1 (Time=0 to 15 mins) confirms the sample contained approximately 3% water. This is confirmed by the respective mass losses (as per stage 1). Stage 2 (increase to 900ºC, time = 15-70 mins), -a slow evaporation mass loss is observed of around 45%. Stage 3: (time = 70-95 mins) air was introduced (temperature increase to 925ºC): the carbonaceous material was combusted (mass loss of 9%) leaving an ash residue with a mass of 43%.

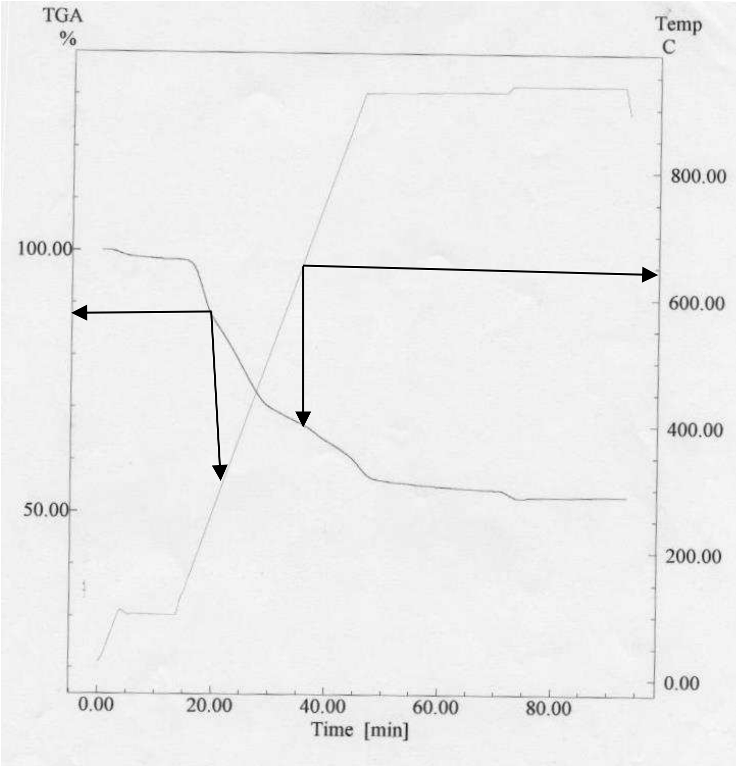

Figure 12: TGA analysis of fouling from the rear face of the B747-400 heat exchanger (Wright 2013).

Description of Figure 12 (rear face): Stage 1 (Time=0 to 15 mins) shows the sample contained approximately 3% water. Stage 2 (time = 15-70 mins), a slower evaporation mass loss was observed with a mass loss of 42%. There is less organic material, and this material evaporates at a slower rate that fouling on the front face. Stage 3: air introduced (increase to 925ºC, time = 70-95 mins): the carbonaceous material was combusted with a mass loss of 2%, leaving an ash residue of 53%.

From the analysis and comparison of the TGA (Figures 11 and 12), the following conclusions may be drawn. Both the front and rear face samples contained similar quantities of water. The rate of evaporation for the front face was much higher than that of the rear face, thus suggesting the front face contains more volatile organic debris. The front face has a slightly higher concentration (by mass) of organic material. The carbon content of the front face is much higher (9%) compared to the rear face (2%), thus the majority of the organic foulant is adhered to the front face of the aircraft PFHE. The ash residue of the rear face is greater in mass content (52%) than that of the front face (43%), thus foulant from the rear is less carbon based as the material has passed through the PFHE. Therefore, the front face of the exchanger contains higher levels of organic material deposits (as confirmed by TGA analysis) compared to the foulant materials collected from the rear face.

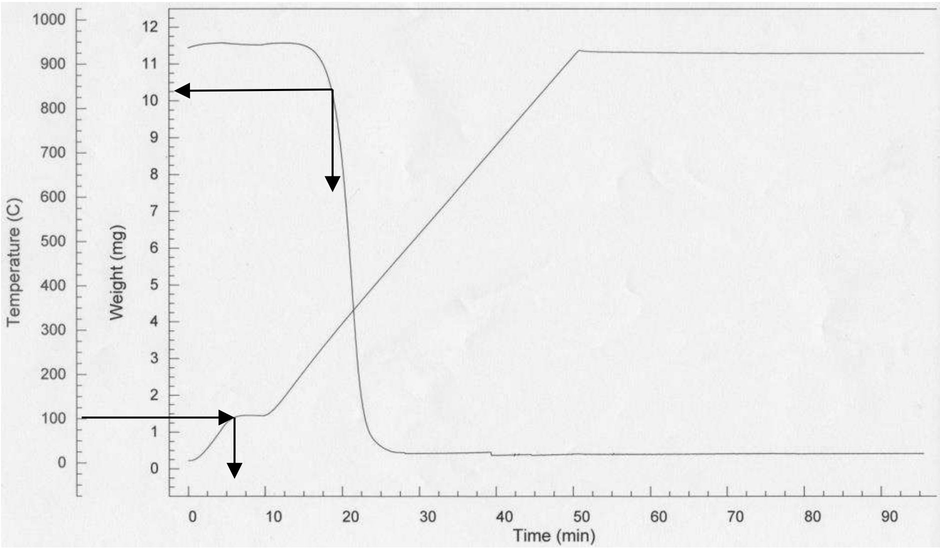

Figure 13: Aeroshell 500 turbine lubrication oil TGA (Wright 2013).

As oil leaks from outside the aircraft are often drawn into the ventilation and cooling systems, their presence causing operational difficulties. It was suspected that the front face fouling may contain engine lubrication oil contamination, a sample of 'Aeroshell 500' turbine oil was sourced and analysed using the TGA method (Figure 13). No mass loss was initially viewed as the sample was raised to a temperature of 105°C, thus suggesting the sample was free from large quantities of water. It can be seen from Figure 13, that mass loss begins to significantly occur at temperatures in excess of about 220°C, with a rapid evaporation taking place. At a temperature of about 400°C, all the volatile compounds have evaporated leaving a residue. When air is introduced to the sample, significant mass loss is not observed, suggesting that the carbonaceous compounds evaporated at lower temperatures, between c. 220 to 400°C.

Further to the thermo-gravimetrical analysis, small quantities of B747-400 front face fouling material was adhered to a series of scanning electron microscope stubs using conducting carbon tape. A high definition Philips FEG SEM unit was selected to perform the analysis, the stubs were first coated using platinum 3 nm splutter coating. The initial low magnification (1,500) view of the material adhered to the stubs (Figure 14), the image indicates that the fouling material was carbonaceous, and contained both fine and ultra-fine materials.

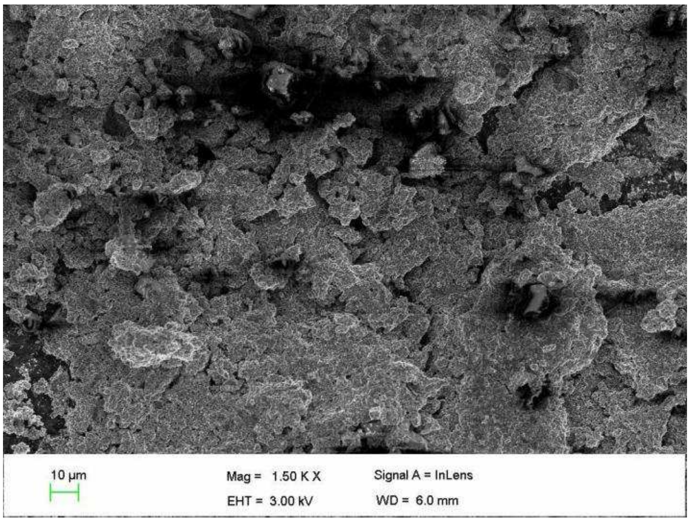

Figure 14: A typical SEM B747-400 front face at a low resolution (1,500 magnification) (Wright 2013).

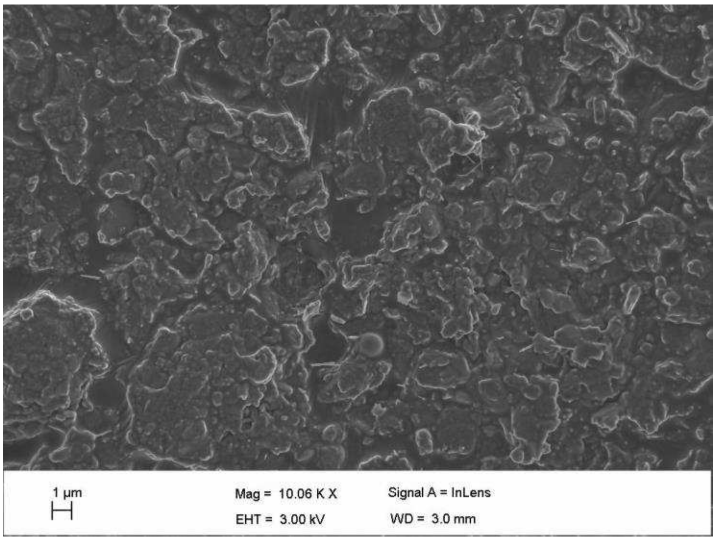

Figure 15: A typical SEM image of B747-400 front face fouling at medium resolution (10,600 magnification) (Wright 2013).

When magnification was increased to 10,600 magnifications (Figure 15), the carbonaceous structure is viewed more clearly, showing a layered effect where material appears to have been sheared. As the fouling was 'baked' onto the B747-400 exchanger matrix face, mechanical effort removed the 'baked on solid' materials. Upon closer inspection of sites of interest at 100,000 magnification, (see Figure 16), the ultrafine particulates are observed to be adhered to other larger particles. This structure is typical of organic carbonaceous particulates from burnt and un-burnt hydrocarbons associated with the transportation of particulate matter pollution.

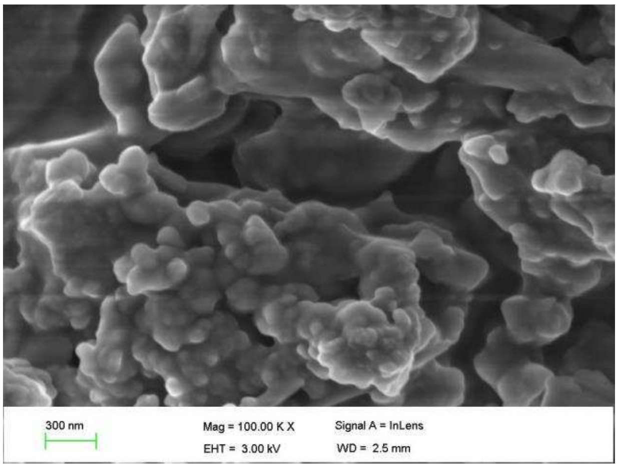

Figure 16: A typical SEM image of B747-400 front face fouling at high resolution (100,000 magnification) (Wright 2013).

Elemental analysis of the ‘MAIN’ front face samples was conducted in the SEM equipment using Energy Dispersive Spectroscopy (EDS) in the FEG-SEM unit. Spectra’s of elemental energy bands were collected (Figures 17 and 18). The elemental X-ray analysis (i.e. EDS) of all the sample sites (Figures 17 and 18) suggests that silicon and oxygen is present (SiO_2), and likewise sodium and chlorine (NaCl). Zinc compounds are used in lubrication oil for aircraft engines, likewise, if used, lubrication oil contamination of the exchanger existed, ferrous compounds would be likely and this was found to be the situation (Fe traces). Additional metal traces included Al, Be, K, Mg, Ti and Zn: the metals are believed to come from different sources, mostly attributed to gas turbine operations.

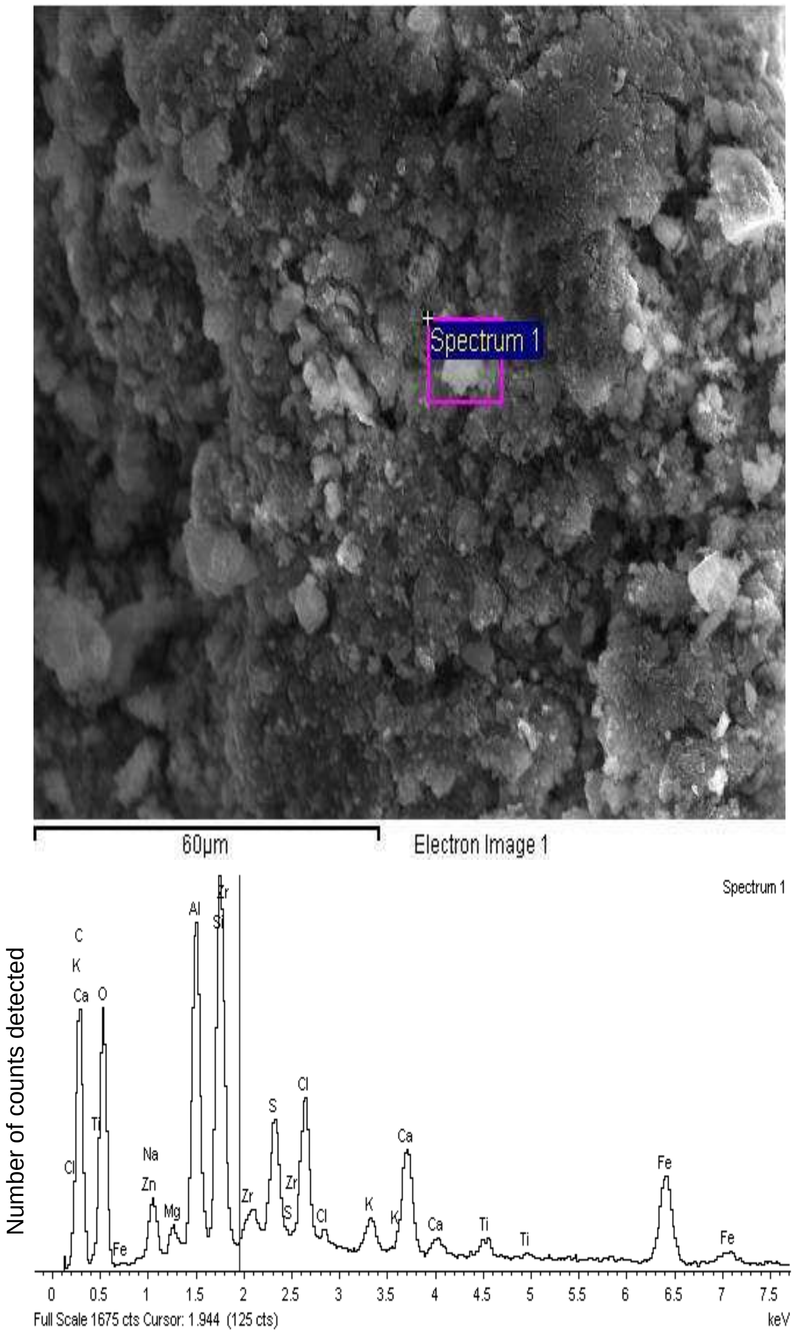

Figure 17: A typical EDS B747-400 front face elemental analysis at area one (Wright 2013).

Gas turbines are known to have thermal protective coatings in the combustor linings in order to allow for the higher burn temperatures of the fuel air mix. This lining is very fragile and requires regular boroscope inspection, as cracks or removal of the lining would result in the combustible gases burning through the combustor lining very quickly and this causing an uncontained engine fire. The linings are commercially sensitive as the operation and efficiency of the gas turbine engine is closely linked to the combustion temperatures for respective engines. It is believed that the combustor liners contained yttria stabilised zirconia (ZrO_2 with Y_2O_3).

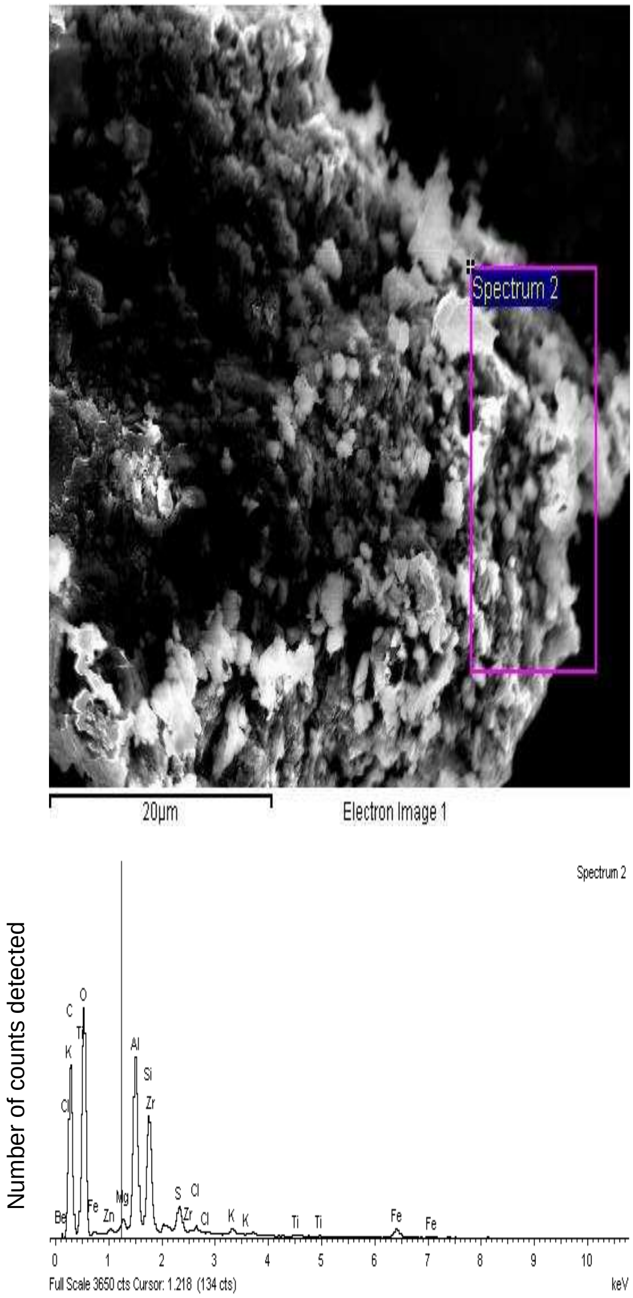

Figure 18: A typical EDS B747-400 front face elemental analysis at area 2 (Wright 2013).

The presence of zirconium was identified in the EDS spectra (Figures 17 and 18) of the fouling material: the EDS spectra's were forwarded to a UK based Gas Turbine coatings specialist for review and confirmation. They confirmed that small quantities of lining are detected in the fouling samples, as the lining material is ejected typically during the formation of the particulate matter in the combustor – they stated that this is more evident during the starting of the engine. It was also confirmed that the gas turbine compressor abradable linings are constructed from aluminium boron nitride materials. Boron is not observed on the EDS spectra as the X-ray detector has a conventional window, thus the low energy emitted from boron cannot be detected as the electron yield is very low. However, aluminium is abundant in quantities (as observed from the strong spectral peaks). This suggests that small abraded particulate has passed into the compressor gas stream and through the hot section of the gas turbine: the material is ejected to atmosphere in the engine exhaust.

From this analysis, it is proposed that during the combustion of kerosene in the gas turbine, small quantities of soot particulates are produced with a maximum rate of production during the start-up (as confirmed by visual observations of live commercial aircraft gas turbine engine starts at Leeds Bradford International Airport): during soot production, small quantities of thermal barrier coating (yttria stabilised zirconia) are also ejected as small particulate matter. The abradable gas turbine compressor linings produce larger amounts of particulates, which pass into the combustion stream and exit from the exhaust.

An observation made by the corresponding author at the time of fouling material collection from the aircraft undergoing maintenance activities, was the front inlet face of the (fouled) PFHE resulted in the individual finned passages becoming either reduced in size or completely blocked. The fouling that had deposited on to the PFHE was mostly located on the front inlet face, with lesser quantities that appeared to be exiting from the rear. The porosity of the fouled PFHE was reduced.

7 Gas turbine operation as a source of pollution

Aircraft engine oil consumption is usually considered to be relatively steady during engine operations (c. 1% by volume to fuel burnt) (Andrews et al. 2009). Lubrication oil is known to be combusted in a gas turbine engine during the start sequence in much higher quantities compared to other phases of the flight. To start a typical gas turbine, the high speed shaft is motored (by the starter) to approximately 10% speed. When this speed is achieved, the flight crew advance the power lever of the respective engine from the 'Off' detent to the 'GI' (ground idle) detent, which permits the high pressure Jet A1 fuel to flow to the primary fuel burners / atomisers on the combustor and simultaneously the fuel is ignited by the ignition system. The engine speed accelerates to approximately 50%, at which point the secondary fuel flow from the duplex burners enters the combustor. At a manufacturer's defined value, the combustion of the engine is deemed stable and this power setting is defined usually as the ground idle speed. During the start sequence, the engine 'customer' bleed air manifold is unable to supply the necessary differential pressures, as the engine performance has not fully reached the ground idle performance levels. This results in a lower than normal differential pressure, within the bearing cavities inside the core of the engine. The differential pressure is required to 'blow back' lubrication oil from the bearing cavity across a labyrinth seal to an oil scavenge cavity (see Figure 19).

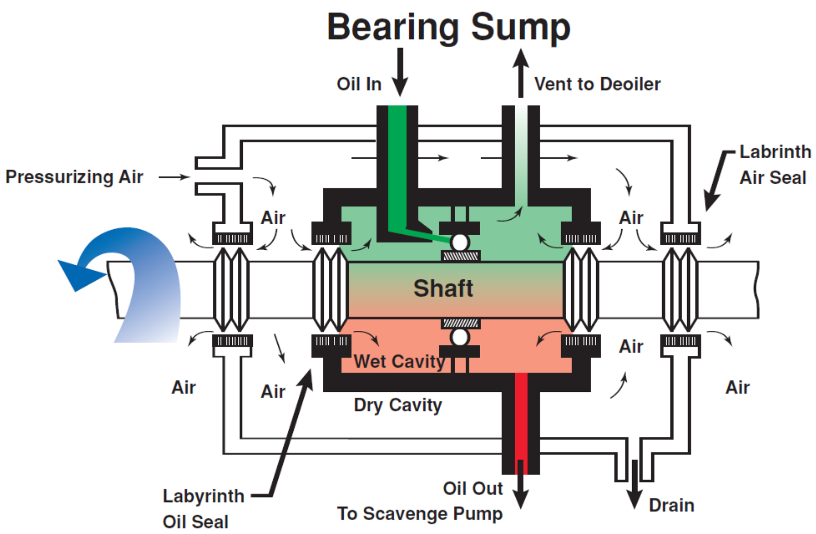

Figure 19: Diagram of the pressurised lubrication oil sump shown with four labyrinth seals to prevent oil loss (ExxonMobil 2009).

The absence of a sufficient bleed air differential pressure in an engine start sequence results in quantities of lubrication oil passing from the wet cavity across the labyrinth seals, and entering the dry cavity and the core including the hot section of the engine. This results in large quantities of 'black smoke' being emitted from the engine exhaust during this start sequence. An example of the complexities of labyrinth seals (Figure 20) illustrates a modern triple spool gas turbine, which requires high pressure air to force lubrication oil across two labyrinth seals within a key bearing cavity.

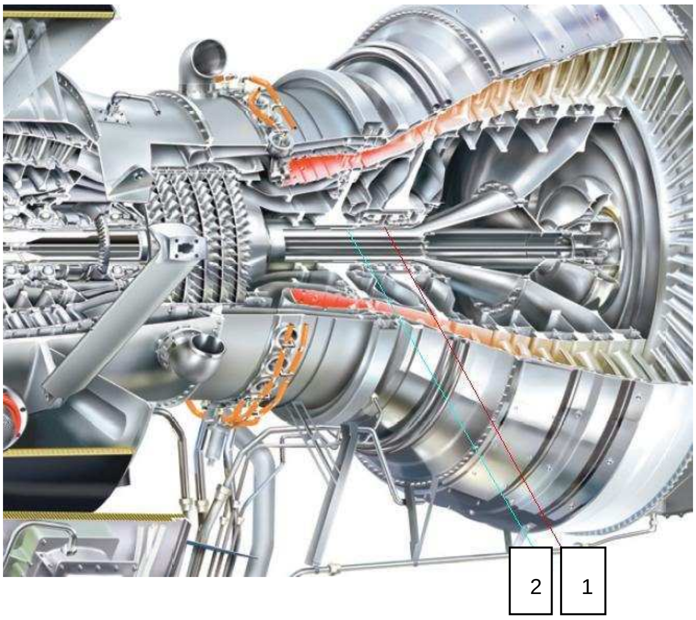

Figure 20: Cut away drawing of a Rolls Royce Trent 500 engine showing the intermediate spool shaft labyrinth seal (1) and the high speed spool labyrinth seal (2) (Rolls Royce 2010).

Whilst the precise formula of such turbine engine lubricants are commercially sensitive, the overall performance of the lubricant in a wide range of operational temperatures implies that organic based additives (e.g. Poly-Aromatic Hydrocarbons (PAH) and other complex organic compounds) are present in the oil. Thermal degradation of the turbine oil yields not only gaseous fraction of the oil derivatives (i.e. very long chain alkanes >20 carbons), but also shorter organic molecules from the plasticiser additive via the evaporation of the fluid (Wright, 2013).

Figure 21: Photograph of the Paradise Airport, USA, air quality remote monitoring station (Wey et al., 2006).

The concentration of particulate matter has been published within the environmental data for London Heathrow Airport, at various locations around the airfield including at a remote site close to the perimeter fence. Whilst the highest recorded concentrations of PM_{10} at London Heathrow Airport in 2003 were recorded slightly above 100 μg/ m^3, these recorded values are representative of the concentration measured by the technical equipment at the specific remote site within the airport perimeter. Recording the particle concentration requires a scanning mobility particle sizer (SMPS) attached to a classifier and condensed particle counter, and these devices are usually located within a movable static caravan (Figure 21) if a portable sample is required. The location of the sensing equipment at Heathrow is not specified in terms of the distance from the emission sources (aircraft), but it can be assumed that the minimum distance between the static caravan and the aircraft must be greater than 200 m, being the minimum safe distance behind an aircraft due to 'jet blast.'

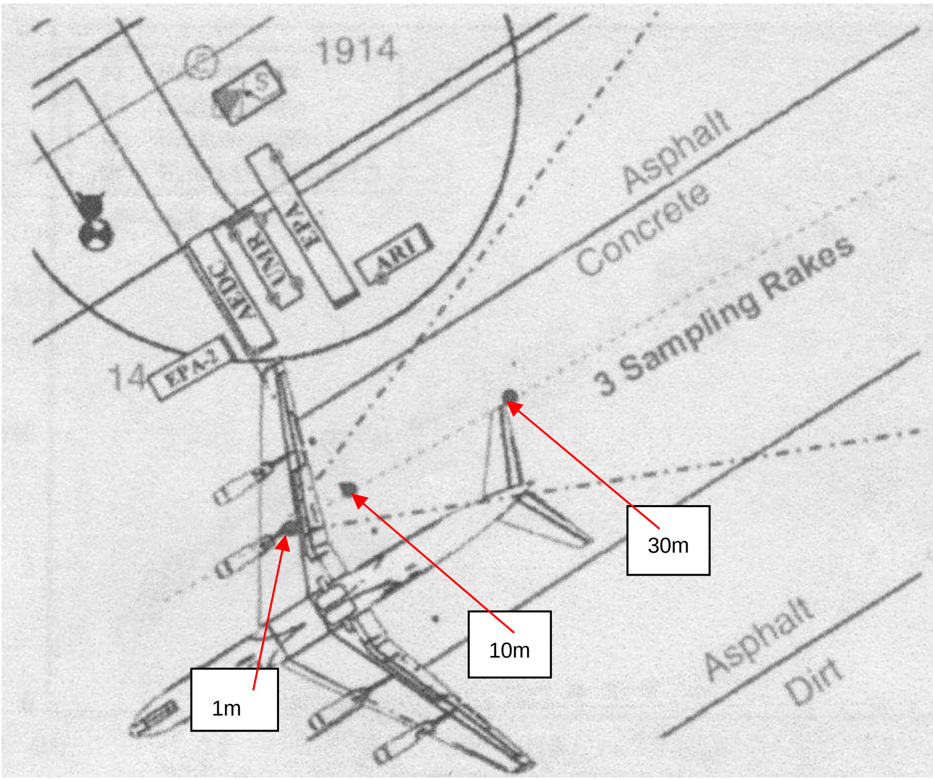

Figure 22: Test aircraft layout including sampling locations (engine number 3) at 1 m, 10 m and 30 m, (Wey et al., 2006).

A CFM 56 engine on a tethered test aircraft was used to determine the effects of particle emission, monitored at distances of 1 m, 10 m and 30 m (Wey et al. 2006). The use of the test equipment in this study is different to the other airfield sampling methods, as the test aircraft was tethered, the sampling rakes (to collect the gaseous particles) were bolted to the apron surface, and the rake sample outlets were connected to the test equipment via long heated sample lines, positioning the various test equipment to the side of the aircraft, thus away from the effects of the jet blast (Figure 22).Dilution of the fouling source from the engine exhaust with ambient air was cited by Wey (2006) to be 1:10 ratio for the 10 m samples and 1:30 for the 30 m samples (Figure 21). The results from the CFM 56 engine tests indicated that as the distance increases from the rear of the engine, the size particle count decreases and the size profile changes increasing the particle sizes (up to 300 nm), which is attributed to VOC particle coagulation.

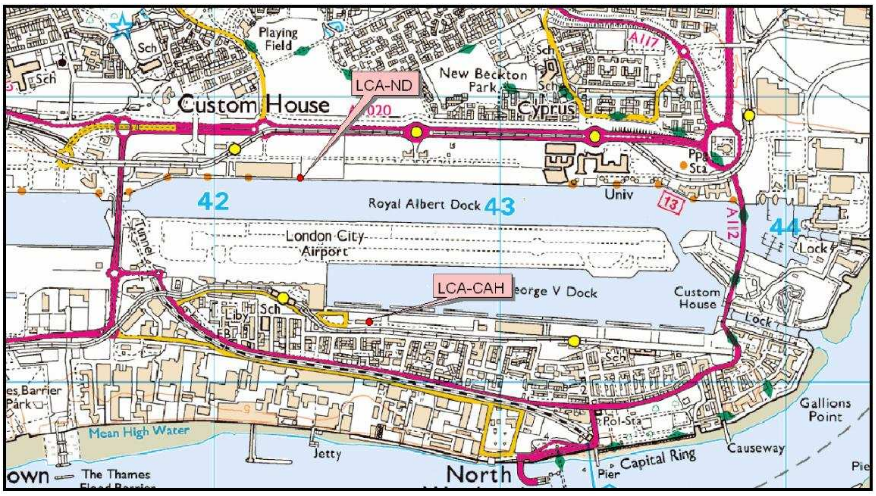

Figure 23: Automatic monitoring location of particulate matter at London City Airport (London City Annual Report 2010).

London City Airport has one PM_{10} automated monitoring station (Figure 23) located on the airport perimeter, indicated by a red dot and labelled 'LCA-CAH' corresponding to the roof mounted position of Civil Aviation House. The annual mean recorded concentration of PM_{10} at LCA-CAH was 22 μg/ m^3, which although is significantly lower than Heathrow's perimeter monitoring site can be attributed (Wey et al. 2007) to the location of the sensing equipment.

The concentration of fouling that live aircraft are exposed to whilst operating at an airport is higher than the reported figures presented by both Heathrow and London City Airports, as the distance between the aircraft taxiing are in the range of 50-75 m (Figure 23). It is more likely that as the aircraft depart from the airport gate or parking stand, the concentration of particulate matter will be significantly higher than those reported by the airfield operators, due to the dilution ratio between the emission source and the monitoring position. The aircraft that are positioned directly behind other aircraft in a queue (Figure 23, foreground) and will be subjected to very high levels of particulate concentration and possible exposure to this fouling material. Figure 24 illustrates that the rear most aircraft (in the foreground) is following four aircraft which are directly ahead of the aircraft: all the aircraft in the photograph are running their engines and also the APU, thus producing PM. The close proximity formation of the queuing aircraft appears to encourage the fouling of the packs, as the "ram" air inlet is being supplied with a heavily fouled air source (from the aircraft in front).

Figure 24: Photograph of several commercial aircraft queuing on a taxi way prior to take off at London Heathrow Airport (BAA 2010).

Effectively, as these aircraft line up in such formations (Figure 24), with the packs running on the ground, the aircraft are simply 'vacuuming' the heavily fouled "ram" air directly onto the pack PFHE. When a threshold is reached and the PFHE becomes sufficiently fouled, it is plausible that the "ram" air flow, i.e. the mass flow, will be insufficient to provide an adequate cooling flow to the cold side of the PFHE, thus as the pack experiences the negative feedback of the thermal runaway, an overheat of the pack results. The aircraft, which is still on the ground in the queue, is then required to return to the stand and rectify the failure (taking up to 8 man hours to change the pack).

8 Conclusions

The main conclusions that can be drawn from this study show that the “ram” air cooling within the pack system encourages the deposition of PM on the PFHE surfaces. The range of aerosol particles is from ultra-fine (1 nm) to larger PM_{10} (10 μm).

The monitored and published levels of airborne PM_{10} around London City and London Heathrow Airport have defined sources of PM_{10} produced by the transportation and aviation sector, to be road transportation, aircraft operations and associated aircraft equipment.

Aircraft engines and APU operations are a known source of PM fouling. The concentration of fouling decreases with the increase in distance.

There are no recorded values of PM fouling on the active taxi ways at London Heathrow airport or on the apron (i.e that would affect aircraft on the ground). The monitoring equipment has been located a considerable distance from the aircraft sources, due to safety requirements.

Fouling analysed from commercial aircraft PFHE indicates a carbonaceous structure containing numerous additional elements, implying multiple sources. The structures observed from SEM analysis indicates that ultrafine particulates are adhering to form larger structures, and this foulant adheres to the ECS PFHE by impact. Elemental analysis indicated that gas turbine operation is a significant source of potential fouling, including abradible panels and thermal barrier coatings from within the gas turbine engine. As the fouling builds on the PFHE inlet face, the passage size of the channel reduces as the deposits adhere.

When an aircraft gas turbine is started, lubrication oil is consumed within the engine. The oil is initially vaporised, and if the fumes pass into the combustor, they are burnt. Thus, the fouling produced at an airfield includes lubrication oil vapours. The oil appears to contribute to the adhesion of the fouling to the PFHE.

When aircraft queue in a formation during the taxiing phase, the individual aircraft are subjected too much higher levels of PM (from the aircraft emission directly ahead), and this fouling can be ‘sucked’ into the “ram” air inlet cooling for the packs. The fouling is known to affect the PFHE within the ECS pack, thus the requirements for regular pack PFHE replacements as a part of the approved aircraft maintenance schedule.

Published ECS optimised models make a heavy emphasis on the physical characteristic of the pack, but do not take into account the effects of fouling or system failures.

This paper has revealed that there are few published or known materials about the particulate matter fouling / deposited on aircraft PFHE within the ECS pack.

Fouling analysed that was obtained from commercial aircraft pack PFHE confirms that the sources of fouling are both naturally occurring and from aircraft operations. The fouling materials obtained from the pack PFHE, source analysis of this material can be attributed to the aircraft operation include burnt/un-burnt fuel, turbine engine lubrication oil and tyre debris: gas turbine engine wear is also a contributing source of particulate matter. The formation of aircraft queues whilst on the ground, could be a factor to explain why some aircraft PFHE foul more readily than others, as the exhaust emissions from aircraft at the head of line can be more easily ingested by the pack “ram” cooling stream.

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