A cost-efficient design change for enhancing the aircraft cabin air supply

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The goal of this paper is to propose an alternative means of heating and pressurizing modern airliner cabins. It provides a personal overview of bleed air, its uses and problems, and of aircraft gas turbine engine types. This sets the scene for reconfiguring the present bleed air system, without major redesign and certification issues.

1. INTRODUCTION

The PW JT3-3D-powered DC8 did not use engine bleed air for cabin pressurization and air conditioning. It was fitted with two nose "chin scoops", each of which had three separate intakes (Figure 1). A small amount of engine bleed air was, however, used to spin the turbo compressors (TCs) that drew in and compressed fresh air, raising its temperature in the process. That air then flowed through the two heat exchangers and Freon units for delivery, at controlled temperature, into the cabin pressurization and air distribution system.

Figure 1. The nose of the DC8. On each side, the large centre opening was the intake for the respective left and right air-to-air heat exchangers; the two smaller holes were individual intakes for the four turbo compressors.

In later, "advanced" versions of the DC8, the JT3s were replaced with more efficient CFM 56s and the chin scoops were modified to close the TC inlets, the TCs and heat exchangers being replaced with "packs" to use direct engine bleed air for air conditioning and pressurization. At the time that was considered to be progress!

2. HOW DOES THE MODERN BLEED AIR SYSTEM OPERATE?

Bleed air is a term that is frequently discussed when it comes to aircraft systems, particularly when a cabin air event ("fume event") is involved, but what exactly is bleed air and what does it do on the aircraft?

2.1 The Brayton cycle

The basic operation of the gas turbine is a Brayton cycle with air as the working fluid. Atmospheric air flows through the compressor that brings it to a higher pressure; energy is then added by spraying fuel into the air and igniting it; the combustion generates a high-temperature flow. This high-temperature pressurized gas enters a turbine, producing a shaft work output, which is used to drive the compressor; unused energy comes out in the exhaust gases, which can be repurposed for external work, such as directly producing thrust in a turbojet engine, or rotating a second, independent turbine (known as the power turbine) that can be connected to a fan, propeller, or electrical generator. The purpose of the gas turbine determines the design to achieve the most desirable split of energy between the thrust and shaft work. The fourth step of the Brayton cycle (cooling of the working fluid) is omitted, as gas turbines are open systems that do not reuse the same air.

2.2 So what is bleed air?

"Bleed air" is the term used for the air that is "bled" from the compressor stages of a gas turbine engine. At this stage the air has a temperature of around 200–250 °C and a medium-high pressure; its energy is used to power several airframe systems, including but not limited to the air conditioning (Figure 2).

The use of bleed air is common throughout commercial aircraft and helicopters today as it is a readily available source of energy. If the engines work proficiently, bleed air will be available. Its most useful qualities are heat and pressure. Heat is often used for anti-ice and deicing systems and the pressure is used for flow services such as the provision of cabin air.

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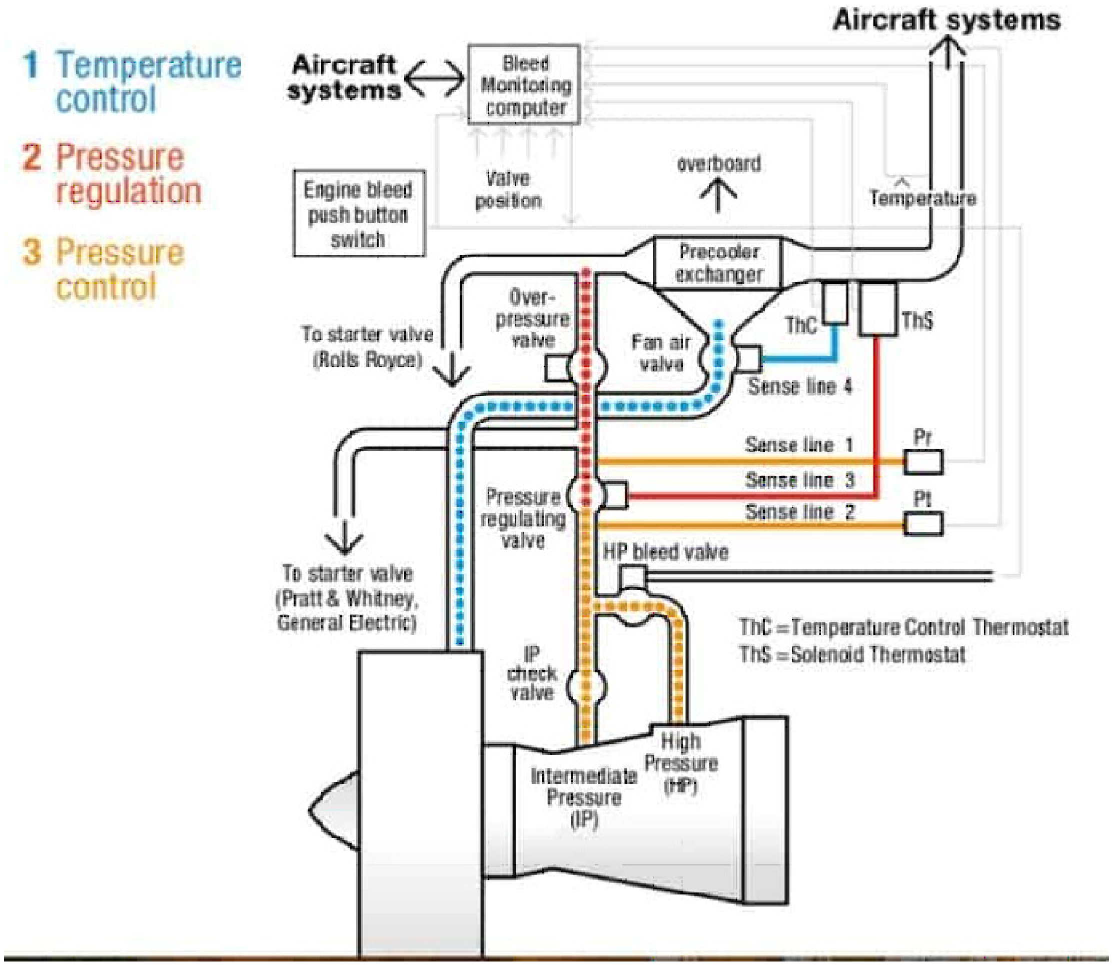

Figure 2. Schematic diagram of a typical aircraft bleed air system.

2.3 Anti-ice

Icing conditions exist both on the ground and whilst airborne in most regions of aircraft operations. Ice accretion can occur between +10 and –50 °C when moisture is present such as in rain or as multimers in a cloud. This water can condense and freeze on the cold wings, especially on their and other leading edges, changing the profile shape and upsetting the lift characteristics designers have so carefully created.

With the aid of bleed air, the threat of ice accretion and the dangers this brings in flight can be mitigated. There are numerous ways to rid an aircraft of ice, but bleed air is one of the most commonly used methods.

2.3.1 Anti-ice via air tubes

By routing hot bleed air via piccolo tubes inside the leading edges of the wings, tail surfaces and the engine inlets, the surfaces can be heated to above freezing temperature. Once the warm air raises the temperature of the surface, any ice already formed melts away and further ice accretion is prevented. This is the most common method of ice protection on the majority of commercial aircraft. An exception is the Boeing 787, one of the most efficient aircraft of its size. The aircraft has electrothermal anti-icing for the main leading edges of the wings. This ice protection system is typically seen on lighter aircraft. The use of electrical instead of bleed air helps to decrease fuel burn and improves overall cost-efficiency by eliminating the high-maintenance bleed systems albeit with the penalty of the weight of the additional electrical generation equipment required.

2.3.2 Deicing boots

Turboprop aircraft such as the Dash 8 Q400 cruise at altitudes below 27,000 ft and spend much time in the heavily moisture-laden cloud zones. These aircraft use what is known as “pneumatic boots” to keep their surfaces ice-free. The “boot” is a layer of rubber placed on the leading edge of the wing that is inflated with bleed air to temporarily change the shape of the wing and break off any unwanted ice.

Pneumatic boots haven't changed much in their design since their invention over 80 years ago and are fairly lightweight. Unfortunately they do require regular inspection and maintenance. They can crack when operating; the material deteriorates in ambient conditions, especially due to ozone exposure; and they can be punctured by debris from the runway or ice shed from the propellers.

2.4 Pressurization and air conditioning

Possibly the most important use of bleed air is to enable cabin pressurization and environmental conditioning (Figure 3). Pressurizing the air within the cabin allows us to breathe at high altitudes without oxygen masks; heating it allows ordinary clothing to be worn. Furthermore, oxygen is consumed by human breathing and must be replenished, and the exhaled carbon dioxide must be removed. Air bled from the engine is a readily available continuous source of fresh, hot pressurized air.

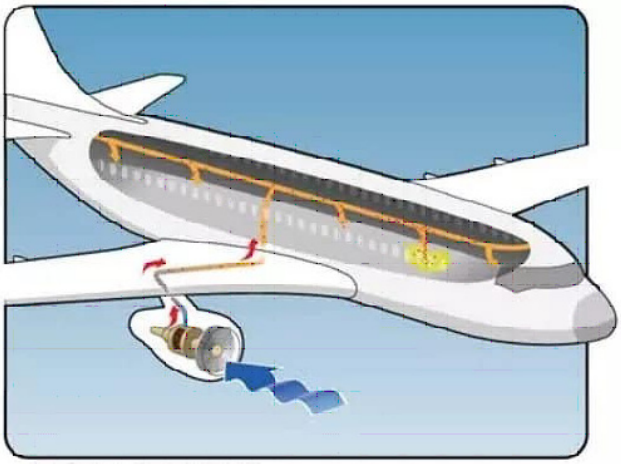

Figure 3. The use of air bled from the main engine to heat and pressurize the cabin and provide a continuous source of fresh atmospheric oxygen.

As mentioned, bleed air temperature can be over 250 °C when it leaves the engine and hence must be cooled via a heat exchanger before it can be circulated into the cabin. Cold air from outside the aircraft is used and passes over the hot bleed air in the air cooler. The primary temperature controller is on the flight deck (Figure 2), although many aircraft provide the capability for altering the temperature from inside the cabin. The temperature selector changes the amount of cool air allowed through the air ducts until the desired temperature is reached.

On twin-engine aircraft, both engines are used to supply conditioned air, although other sources of bleed air are available at various stages of flight. Four-engine aircraft such as the BAE 146/RJ bleed from all four engines. On the ground, many airports in hot locations provide air through a ground supply, identified by a large yellow pipe when the aircraft is parked on the stand. This provides air conditioning without the need to use the auxiliary power unit (APU), thus keeping noise and emissions low. The APU is more commonly used, however, as external air is not always available. Located at the rear of the aircraft, the APU is a small, low-technology engine that works in the same way as the larger main engines, creating its own bleed air. With the main engines switched off this is the independent source of air conditioning. Conversely, the APU is usually idle when the main engines are running.

2.4.1 Depressurization

Failure of the bleed air system can lead to cabin depressurization, such as on a recent A319 flight from Cape Town to Johannesburg. The crew received a warning of the failure of engine no 1's bleed system and took the appropriate corrective actions. Nonetheless the effective cabin altitude began to increase. The crew therefore made an emergency descent according to standard procedures until they reached a safe altitude. At this lower altitude they were then able to start the APU and use it as a source of bleed air to restore cabin pressure, allowing them to continue to their destination.

2.4.2 Hydraulic system reservoir pressurization

Bleed air is also useful in conjunction with the hydraulic system. By pressurizing the hydraulic reservoirs, manufacturers are able to prevent cavitation and the damage it causes. Cavitation occurs when fluid volume demand is greater than the amount of fluid being supplied, leading to bubbles. The fomation of bubbles in the hydraulic systems is a very serious matter—it can cause major failures of pumps and motors. When the bubbles implode they erode and damage nearby surfaces. The implosion is a violent process that generates highly localized, large-amplitude shock waves. Pressurizing the reservoirs with bleed air is an effective way of preventing bubble formation within the fluid.

2.5 Engine start

For operational and ground safety reasons, turbofan engines are normally started on the pushback from the airport gate prior to taxi; the operation can take 2–3 minutes or more. To do this the aircraft must have an operational APU supplying both electricity and bleed air. (If the APU is unserviceable, the air must be provided externally from a unit on the ground. The APU itself is started using an electric starter motor that runs off the aircraft 115 V electrical system.)

When the start sequence is initiated, bleed air is sent from the APU to the accessory gear box, causing the various shafts within the first engine to rotate. This is when the "suck-squeeze-bag-blow" sequence begins. Once combustion within the engine becomes self-sustaining the igniters are switched off and engine start is complete. Once this first engine is running, its bleed air can be used to start the second engine—this is known as a cross-bleed start—and the APU can be switched off as it is no longer needed as a source of bleed air.

3. ISSUES WITH USE OF BLEED AIR

As one would expect, various hazards are associated with the use of extremely hot and high-pressure air. One pitfall of the bleed air cabin air system is that any contaminants from the engine are potentially circulated around the cabin. For instance, hot oil may leak from inside the engine seal and bearing locations into the bleed air supply. Depending on seal design, this can be continuous at a very low level ("weeping" seals), or intermittent (e.g., when engine operating parameters suddenly change). Due to the high air temperature, the oil may be pyrolysed (or even oxidized, despite the presence of antioxidants in typical turbine oil formulation). Hence not only oil but also pyrolysed oil can be mixed with the air being fed to the cabin, leading to a burning smell or even smoke entering the cabin if the seals have deteriorated. Furthermore, if the engines have been incorrectly washed during maintenance, residue from the engine cleaning chemicals can also be fed into the cabin via the bleed air. Flight deck and cabin crews are trained to deal with such contamination scenarios appropriately to ensure their safety and that of the passengers, but fume events have raised concerns about the quality of cabin air and the long-term effects it might have on the health of aircrew and frequently flying passengers.

Thankfully such "fume" incidents are much less frequent on newer aircraft than formerly, due to advanced technology such as new Hydro Pad engine seals and improved HEPA and carbon filters in the cabin air supply system (these filters use layers of glass fibres and activated carbon-based material to remove typically 99.7% of particles within the air, including harmful microbes such as some strains of SARS-CoV-2). Such modifications can be retrofitted to older aircraft as an aid to make flying safe. On the other hand the tendency to replace regular maintenance schedules with on-demand on-wing maintenance and overhauls far less frequent than formerly has tended to counter these advances, not least since replacement of a deteriorated oil seal cannot be accomplished on-wing. Improved filters are only a stop-gap fix to horrendous ongoing issues. Hence, a new approach is required that could resolve the problem without major redesign and certification issues.

4. AIRCRAFT GAS TURBINE ENGINE TYPES AND CONSTRUCTION

Gas turbine engines are classified according to the type of compressors they use. There are three types—centrifugal flow, axial flow, and centrifugal-axial flow. Compression of inlet air is achieved in a centrifugal flow engine by accelerating air outward perpendicular to the longitudinal axis of the machine. The axial flow engine compresses air by a series of rotating and stationary airfoils moving the air parallel to the longitudinal axis. The centrifugal-axial flow design uses both kinds of compressors to achieve the desired compression.

The path the air takes through the engine and how power is produced determines the type of engine. Four types of gas turbine engines are used to propel and power aircraft. They are the turbojet, turbofan, turboprop, and turboshaft.

4.1 Turbojet

The term "turbojet" was initially used to describe any gas turbine engine used in aircraft. As gas turbine technology evolved, other engine types were developed to take the place of the pure turbojet engine, which was first developed in Germany and England prior to World War II and is the simplest of all jet engines. The turbojet engine has problems with noise and fuel consumption in the speed range that airliners fly (around 0.8 Mach). These engines are limited in range and endurance and today are mostly used in military aviation.

The turbojet engine consists of four sections—compressor, combustion chamber, turbine section and exhaust (Figure 4). The compressor section passes inlet air at a high velocity to the combustion chamber. The combustion chamber contains the fuel inlet and igniters for combustion. The expanding air drives a turbine, which is connected by a shaft to the compressor, sustaining engine operation. The accelerated exhaust gases from the engine provide thrust. The basic operations are: compressing air, igniting the fuel–air mixture, producing power to self-sustain the engine operation, and yielding exhaust for propulsion.

Advantages of the turbojet engine:

- Relatively simple design
- Capable of very high speeds
- Takes up little space.

Disadvantages of the turbojet engine:

- High fuel consumption
- Loud
- Poor performance at slow speeds
- Limited in range and endurance.

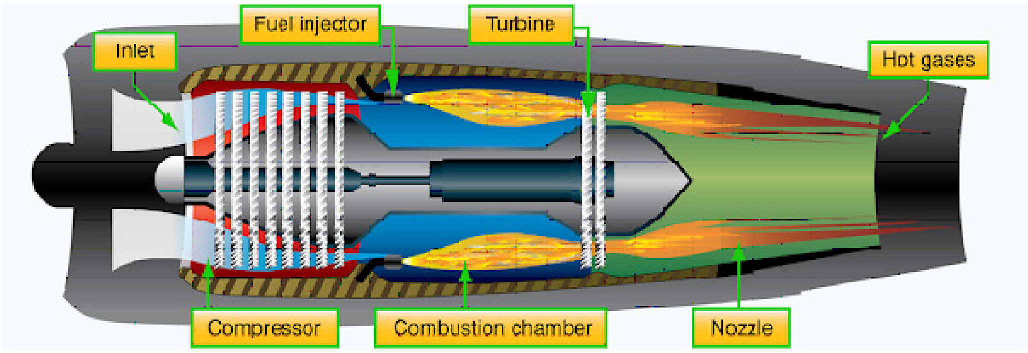

Figure 4. Idealized turbojet engine.

4.2 Turbofan

Turbofans (Figure 5) were developed to combine some of the best features of the turbojet and the turboprop. They are designed to create additional thrust by diverting a secondary airflow around the combustion chamber. This type of engine is considerably quieter and has better fuel consumption than the turbojet in the usual commercial speed range. Hence, almost all modern designed and certified airliners use turbofan engines.

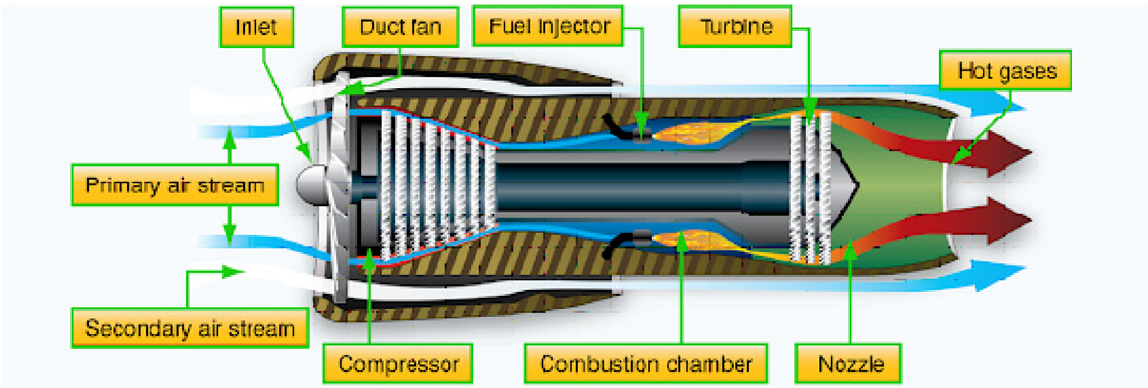

Figure 5. Idealized turbofan engine.

Turbofan engines have a large fan (or set of fans) at the front of the engine that produces about 80% of the thrust. They have more than one shaft in the engine; many are two-shaft engines. Rolls–Royce are the world leader in three-shaft designs, which give a shorter engine length but a slightly heavier dead weight. Multiple shafts are arranged concentrically.

A spool is a compressor and a shaft and turbine that drives that compressor. Two-shafted engines use two spools; that is, there is a compressor and a turbine that drives it and another compressor and turbine that drives it. In a two-spool (-shaft) engine, there is a low-pressure (LP) spool and a high-pressure (HP) spool: the LP one generally contains the front fan(s) and the turbine stages it takes to drive it (them); the HP one is the HP compressor, shaft, and turbines. The latter makes up the core of the engine, and this is where the combustion section is located (and hence is also referred to as the gas generator).

Turbofan engines can be low-bypass or high-bypass. As can be seen in Figure 5, the air generally driven by the fan does not pass through the core of the engine. The amount of air that is bypassed around the core determines the bypass ratio. For example, an engine with a duct fan moving 100 lb/s and a core flow of 20 lb/s has a bypass ratio of 5:1.

Some low-bypass turbofan engines are used in speed ranges above 0.8 Mach (military aircraft). These engines use augmenters or afterburners to increase thrust. By adding more fuel nozzles and a flame holder in the exhaust system extra fuel can be sprayed and burned, which can give large increases in thrust for short intervals of time.

Two different exhaust nozzle designs are used with turbofan engines. The air leaving the front fan can be ducted overboard by a separate fan nozzle, or can be ducted along the outer case of the basic engine to be discharged through the mixed nozzle (core and fan exhaust together). In other words, the fan air is either mixed with the exhaust gases before it is discharged (mixed or common nozzle), or it passes directly to the atmosphere without prior mixing (separate nozzle).

Advantages of the turbofan engine:

- Fuel-efficient
- Quieter than turbojets
- They look awesome!

Disadvantages of the turbofan engine:

- Heavier than a turbojet
- Larger frontal area than a turbojet
- Inefficient at very high altitudes.

Turbofans are the most widely used gas turbine engine for air transport aircraft. The turbofan is a compromise between the good operating efficiency and high thrust capability of a turboprop and the high-speed, high-altitude capability of a turbojet.

5. HOW CAN THE BLEED AIR SUPPLY BE IMPROVED WITHOUT A MAJOR REDESIGN OF THE AIRFRAME SYSTEMS?

The gas turbines are mounted on the aircraft wing by a pylon or at the rear tail. In the former, the bleed air is ducted from the engine compressor into a cooler matrix that is located in the pylon area. The cooler uses air bled from the fan air and then exhausted overboard after passing throught the matrix. It is this area that has to be considered for a change in application of bleeds without requiring major structural design and functional changes to the environmental control system (ECS) operation and control. In more detail (Figure 6), the initial delivery of bleed air is ducted from the HP compressor/combustor offtake ports via a pressure-reducing valve into the heat exchanger located in the shoulder area of the pylon. The exchanger is connected to a supply of fast-flowing air delivered from the by-pass airflow via a scoop arrangement in the ducting behind the fan assembly (Figure 7); it is finally exhausted over the pylon fairing.[1]

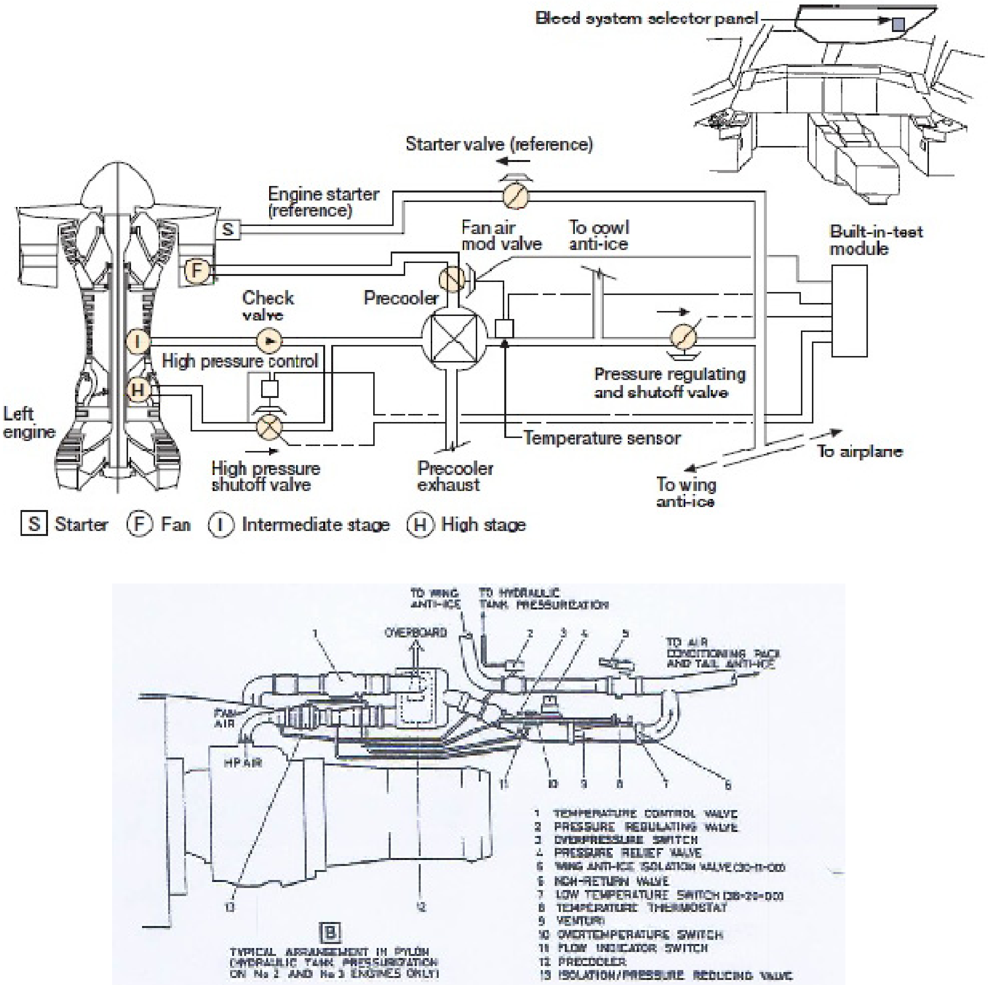

Figure 6. Bleed air systems. Upper panel, generic design. Lower panel, the BAE 146/ RJ.

[1] The arrangements with tail-mounted engines on aircraft such as the Fokker 70/100 or MD90 are similar.

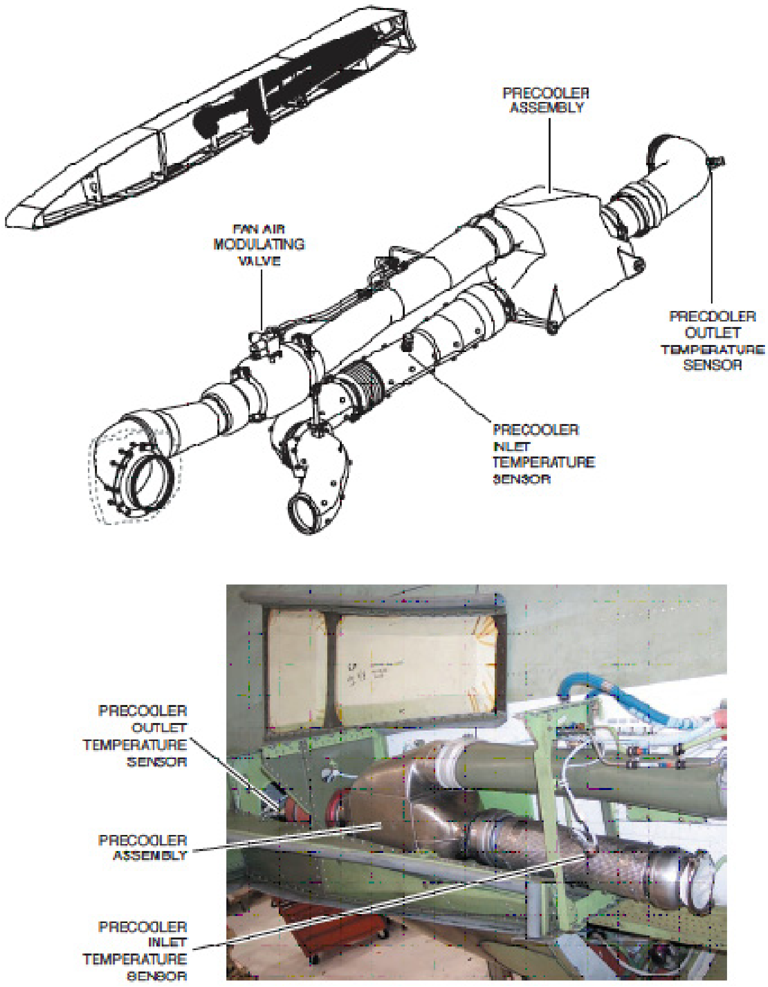

Figure 7. Precoolers. The lower panel shows the new assembly being calibrated on a test rig to ensure that this part of system operates and is controllable according to the aircraft maintenance manual requirements.

The challenge for the aerospace industry is to consider a redesign of this area, namely to in effect *reverse the operation of the heat exchanger. By using fan air as the principal source of cabin air in place of the hot internal bleed air, the main source of chemical contamination would be eliminated. The existing bleed air would be used to heat the fan air to the required temperature*. This would also lighten some of the loading on the compressor section of the engine, which would therefore run more efficiently.

There could be concerns that bleeding air from the fan area would reduce the amount of air available to support engine-efficient bypass operation. The engine control system is designed to measure the inlet temperature (T_2) and the pressure (P_2) at the compressor inlet to the core engine in order to ensure the correct delivery of air mass. The system also measures the pressure in the bypass duct. Hence, the means to measure and control these parameters already exist. The modified cabin pressurization and heating system is expected to fall well within the range under control, hence ensuring adaptation to the modification.

6. AN ALTERNATIVE APPROACH

On 3 June 2016, the Airbus Flight Lab (an A320 aircraft) successfully completed its first flight in Toulouse within “Systems for Green Operations (SGO)”, an integrated technology demonstrator (ITD) organized by the European Union.[2] The aim of the flight was to test extensive on-board electrical systems under real conditions. One of these is the electrical environmental control system (E-ECS) developed by Liebherr-Aerospace Toulouse SAS, the Liebherr company’s centre of excellence for air management systems (Figure 8). The E-ECS is a key element of thermal and power management for increasingly electrically powered aircraft. It is equipped

[2] https://www.cleansky.eu/systems-for-green-operations-sgo

with a new type of motorized turbo compressor (50 kW) which enables external air (bleed-free) to be used directly for air conditioning in an integrated approach. Power electronics provide speed control of the compressor and the capability of synergy with other electrical loads to optimize overall electrical power consumption on board the aircraft.It should be noted that the engines of this test aircraft are configured for test flying purposes and do not represent an in-service aircraft power plant and the associated operational requirements. The additional loading on the engine core has probably not been quantified.

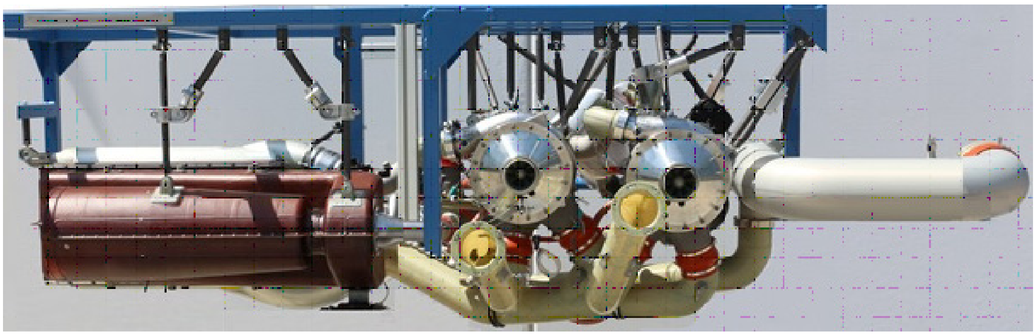

Figure 8. The Liebherr electrical ECS.

7. CONCLUSIONS

The use of bypass air for pressurizing the aircraft cabin is a modification of the ECS without major changes to the current primary design.The change requires the engine manufacturer to ensure that the proposed use of bypass air would have little impact on the thrust requirements for engine operation. The reduction in air bled from the core should make the engine more efficient. Hence, even on purely engineering grounds the return on the modest investment involved in reconfiguring the heat exchangers could be favourable. The main benefit is expected to be the elimination of chemical contamination, mainly derived from the engine oil, in the cabin and the concomitant improvement of air quality, especially the eradication of the endemic problem of "fume events" with the often severe effects on the safety of operations and the health of crews and passengers.

ACKNOWLEDGMENTS

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