DC-9 Environmental Control Design and First Year's Service Experiences

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The design of the environmental control systems for the DC-9 was greatly influenced by the availability of clean engine bleed air for cabin pressurization and by the use of an onboard auxiliary power unit as a source of energy for ground air conditioning. The service problems associated with existing jet transports were scrutinized in depth at the start of the DC-9 design so that marginally reliable components could be avoided and only the proven components and concepts perpetuated. As a result of an intense desire to simplify the system and controls to the optimum extent, engine bleed air is extracted at the lowest practical pressure, air cycle equipment refrigerates the cabin air, and continuous anti-icing is accomplished for the wing airfoil surfaces. A manually operated de-icing cycle removes ice from the horizontal stabilizer. Temperature control for the cabin air supply merely bypasses the refrigeration unit in one step, allowing ram cooling air to continue uncontrolled through the heat exchangers. The results of the first year's airline service experience substantiated the design concepts in that, for the main, excellent reliability was achieved and guaranteed performance was met. Delays in trip departure associated with the environmental control systems will meet the desired goal of 1.2 delays per 1000 departures.

I. Introduction

THE Douglas DC-9 Series 10, small, sleek, twin-engine aircraft of moderate passenger-carrying capacity is shown in Fig. 1. The wing is swept 24° and the configuration features aft-fuselage-mounted engines and a T-tail. It is an aircraft designed for a specific purpose. That purpose does not make it necessary for the aircraft to fly faster, slower, higher, or further than other jet transports already in service.

Then why was this aircraft such a challenge to design, a challenge from the over-all configuration down to the smallest subsystem? The answer lies in its intended use, that of an aircraft designed to be a money-maker on short-haul routes. The DC-9 and its subsystems must be highly reliable, must exhibit a high degree of dispatchability, and be easily maintainable. To attain such design goals, the systems, such as the environmental control systems, must be as simple as practicable, consistent with high performance, and must be easily understood by the line mechanic.

Discussed herein are the considerations and design innovations for the environmental control systems which, for the purposes of this paper, consist of pneumatics (engine bleed air subsystem), cockpit and cabin air conditioning, cabin pressurization, and airframe ice protection. The design was greatly influenced by the availability of clean engine bleed air for inflight pressurization and ventilation and by the addition of the onboard auxiliary power unit (APU) for ground air conditioning use. Although every DC-9 incorporates the APU at the airline option, the air-using systems were required to perform adequately on either a ground pneumatic source or on the engines at idle rpm. Most of the system discussion will apply directly to the Series 10 version, but the few changes required to accommodate the added passenger-carrying ability of the Series 30 will also be noted.

The first year's service experiences with the airlines substantiated the design concepts in that, for the main, excellent reliability was achieved and guaranteed performance was met. There were a few troublesome areas that needed improvement, as would be expected with a new product. Some of the modifications required are also discussed herein. Goals were set for all systems as concerns the part they play in trip departure delay on the theory that if all pieces meet their individual goals, the whole aircraft also will. Variations in trip delay rate as caused by the environmental control systems are presented as a function of time along with explanations for such variations.

II. Design Philosophy

Certain fundamental thinking was applied to system design during the conceptual design phase.

Keep It Simple

Simplicity was the keynote, based upon the intense desire to simplify the system and its controls to the optimum extent. It was readily recognized that any part removed from a system as being superfluous would result in 100% reliability and exhibit zero maintenance for the life of the aircraft. This was

Fig. 1 The Douglas DC-9 aircraft.

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not to say that the environmental control systems were to suffer in performance by being too simple. It did mean, however, that we were to start with a simplified design capable of high performance, and add components only when their additions could be defended as to dire necessity. As an example, the flow control valve was originally conceived merely as a sonic venturi with no moving parts, recognizing that a considerable variation of airflow would exist between extremes of operation. When it was determined that a redundant air shutoff means was required in the event of a failed open pressure regulator, the butterfly and its actuator were added to the venturi and, by proper design, the combination doubled as a flow control as well.

High Degree of Reliability

Complexity to the aircraft subsystems could be tolerated if all components were reliable. Merely buying a part to an engineering specification does not guarantee reliability; service experience is the best yardstick. The service problems associated with existing jet transports were scrutinized in depth at the start of the DC-9 design, hunting for demonstrated reliability in units of similar usage and environment, so that marginally reliable components could be avoided and only the proven components and concepts perpetuated. New methods were not to be invented if existing concepts were successful and modern in performance. Components with a known defect, but otherwise satisfactory, could be utilized by correcting the defect in a positive manner. Hostile installation environments for sensitive components were to be avoided as much as possible since jet-transport service history pinpointed this as a major consideration.

High Degree of Dispatchability

A short-haul aircraft must be capable of dispatch from small city stops under adverse conditions since adequate troubleshooting manpower and equipment are normally based only at larger facilities. Redundant manual controls and position indicators would allow dispatch with certain automatic system failures. With a small penalty, the aircraft could be dispatched with one of its dual automatic systems inoperative. For example, a single bleed air source would require only limiting the flight altitude to 25,000 ft until the dual source is functional again. If a certain state-of-the-art component must be used which has a marginally reliable history, such an item should be installed so that it could be changed in 15 min or less. Wrench flats and position indicators on each critical valve would allow positive positioning of such a part, either open or closed, and would permit locking it there so that a valve failure need not abort the flight in many circumstances. Critical components could be operated by direct cable control having "steel between the hand and the valve to be controlled," so that certain items could be positioned reliably to assure dispatch.

Easily Maintainable

A major consideration in being able to meet scheduled departures was the ability to quickly troubleshoot a system for the offending component and to effect a quick replacement. Troubleshooting is greatly enhanced when the system design is straightforward and easily understood by the line mechanic. In the environmental control systems, this fact was coupled with subsystem testers and data pickup points (both pressure and electrical) to facilitate pinpointing the malfunctioning part. In addition, many of the controls for the bleed air system and ice protection system, as well as all of the refrigeration system hardware, could be located on the spacious tail stub between the engines for easy access in a standup, weather-protected area for maintenance personnel (see Fig. 2). Equipment that might require frequent attention was to be placed so that other parts need be removed for direct access.

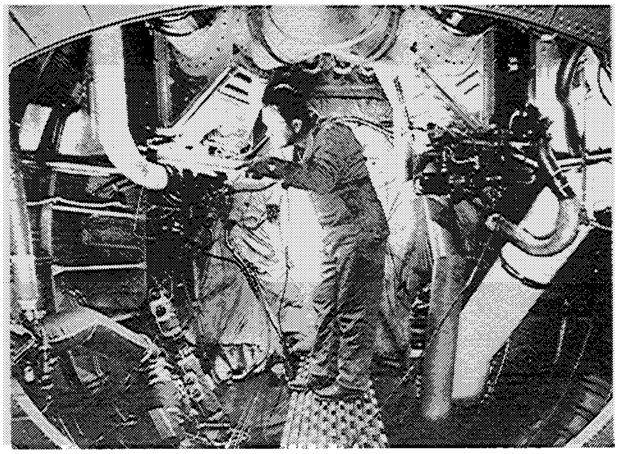


Fig. 2 Environmental control equipment installation in the tail compartment.

III. Design Features

The system description, in conjunction with the discussion of considerations and design innovations, delineates the means by which the goals established in the design philosophy were applied to the DC-9 environmental control systems.

System Description

Pneumatics

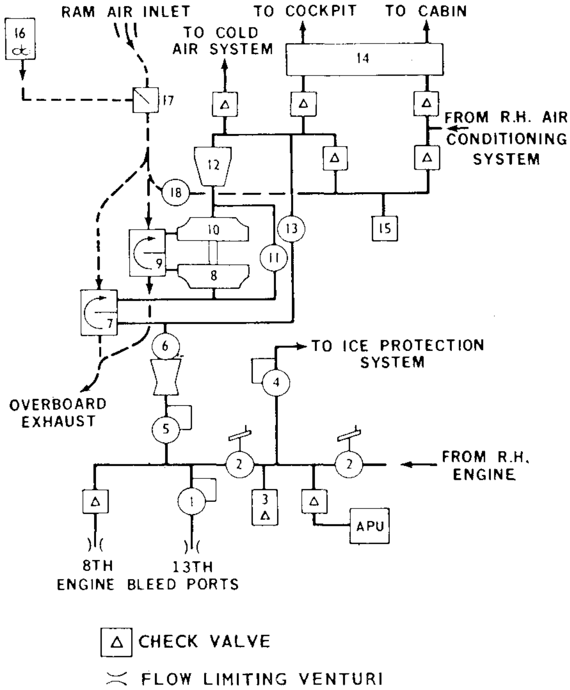
Since the engine manufacturer had taken special precautions to prevent oil leakage past the engine shaft bearing seals into the compressor inlet, the compressor bleed air was judged to be acceptable as breathing air in the occupied areas. Both engine compressors are bled to provide redundant sources of air (see Fig. 3). To provide best economy and limit temperatures to which the air has been heated, air is withdrawn from either or both of two stages, 8th and 13th. The 8th-stage air passes through a check valve into a pneumatic manifold interconnecting the two engines and from which the air-conditioning and ice protection systems and the engine starter receive air. The APU can also supply air through a check valve to the pneumatic manifold as can a ground pneumatic cart. The 13th stage air enters the manifold through an augmentation valve—one for each engine.

The augmentation valve has two modes of operation, one for air conditioning and one for ice protection. When only the air conditioning systems are in operation, the valve serves as an $18\frac{1}{2}$-psig regulator which is permitted to open when 8th-stage air temperature is below 330°F and 13th-stage air temperature is below 550°F. Thus, as long as 8th-stage pressure is less than $18\frac{1}{2}$-psig and the temperature limits are not exceeded, 13th-stage air will enter the manifold and cause the 8th-stage check valve to close. As engine power is advanced, the pressure and temperature rise until either the 13th stage temperature exceeds 550°F or the 8th-stage pressure exceeds $18\frac{1}{2}$-psig. Either condition will cause the augmentation valve to close, and the changeover to usage of 8th-stage air will occur. When ice protection is required, the augmentation valve is positioned in response to pneumatic control pressure established by a pneumatic thermostat and an anticipator operating in parallel. These devices control the valve position and achieve a mixture of 8th- and 13th-stage air at 450°F.

In order to isolate the bleed air sources for redundant air supply when only the air conditioning systems are in use, two manually positioned cable-driven crossfeed valves are installed. Control of the valves is by individual levers in the cockpit.

Air conditioning

Two air conditioning systems are installed, one using air from the left engine, and the other from the right, as shown



1. AUGMENTATION VALVE
2. CROSSFEED VALVE
3. GROUND PNEUMATIC CONNECTION
4. ICE PROTECTION PRESSURE REGULATOR
5. AIR CONDITIONING PRESSURE REGULATOR
6. AIR CONDITIONING FLOW CONTROL VALVE
7. PRIMARY HEAT EXCHANGER
8. COMPRESSOR
9. SECONDARY HEAT EXCHANGER
10. TURBINE
11. WATER SEPARATOR TEMPERATURE CONTROL VALVE
12. WATER SEPARATOR
13. TEMPERATURE CONTROL VALVE
14. MIXING CHAMBER
15. GROUND AIR CONDITIONING CONNECTOR
16. COOLING AIR FAN
17. COOLING AIR SELECTOR VALVE
18. RAM AIR VALVE

Fig. 3 Pneumatic and air conditioning system schematic.

by Fig. 3. Air enters the system through a 23-psig regulator upstream of a flow-control valve. Downstream of the flow-control valve, the air is given two routes to take—through a cabin/cockpit temperature-control valve or through the primary heat exchanger. At the discharge of the primary heat exchanger, a flow split occurs to pass air into the compressor of a "bootstrap" air cycle refrigeration unit and, if required, through the water separator temperature-control valve. From the compressor discharge, passage is through the secondary heat exchanger to the expansion turbine inlet. Discharge from the turbine passes through a screen that collects ice at the dewpoint temperature or at 32°F, whichever is lower. Formation of ice on the screen increases the resistance to airflow, which raises the turbine backpressure to reduce the expansion ratio and increase the discharge temperature. Also, the increase in backpressure causes the pneumatically actuated water separator temperature-control valve to open. The combined effect is to control the amount of ice forming on the screen. After passing through the screen, the air enters a water separator where entrained moisture is removed.

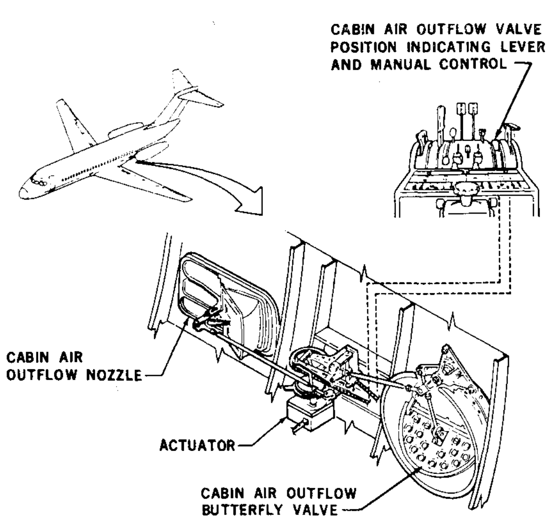


Fig. 4 Cabin pressure control outflow valve.

The cooled air with the water removed is then available to enter the supply duct for individual cold air outlets and to mix with the discharge from the cabin/cockpit temperature-control valve for use in the occupied areas. The temperature-control valve for the left air conditioning system is positioned in response to signals from the cockpit temperature-control system; that of the right to signals from the cabin temperature-control system. After entering the pressurized area, 70% of the air from the left-hand air conditioning system mixes with all of the air from the right-hand system and is distributed to the cabin. The remainder of the flow from the left-hand system enters the cockpit. Exhaust air from the occupied areas is routed under the floor for temperature control of both the electronics compartment and unventilated cargo compartments, and for ventilation of the areas outside the cargo compartments.

Cabin pressure control

The cabin exhaust air is routed toward a double-element outflow valve positioned by a single actuator, as shown in Fig. 4. On the ground, both the large butterfly valve and the smaller thrust recovery nozzle are wide open. Soon after takeoff, the butterfly portion closes, and the control of cabin pressure is by varying the throat area of the thrust recovery nozzle. Position of the outflow valve is established either by an electrically powered actuator or manually by a cable system. The lever for manual control is located on the throttle pedestal in the cockpit and serves the dual purpose of valve position indicator and manual positioning device (as shown in Fig. 4). Power for the actuator is supplied from an amplifier that receives an electrical input signal from a reference to cabin differential pressure sensor. The reference pressure is a pneumatic output of the cabin pressure controller. This controller responds to crew selections as to cabin altitude desired and the rate at which the new altitude is to be approached. Barometric correction to the altitude is also put in by the crew in order to permit accurate cabin altitude control to the landing field prior to touchdown. Features are incorporated, as well, to provide a smooth transition from manual control back to automatic control. Two redundant cabin safety valves are installed to assure that cabin overpressures do not occur. Inward opening check valves in the rear pressure bulkhead prevent application of negative pressure differentials across the fuselage.

Ice protection and rain removal

As shown in Fig. 5, hot air for leading-edge ice protection of the wing and horizontal stabilizer airfoil surfaces is obtained from the crossfeed manifold through a 20-psig regulator. When selected, this air is routed through a normally open shutoff valve to the wing leading edge. A piccolo tube enclosed in the D duct distributes the air spanwise into the D duct. Exhaust from the D duct is by means of passages chemically milled into the wing nose skin and covered by an inner skin. The exhaust passes into the nose cap interior and overboard through openings provided. Periodically during flight in icing conditions and just prior to landing, the wing shutoff valve is closed and a tail shutoff valve opened to supply heat to the horizontal stabilizer leading edge. The tail de-ice cycle is initiated by manually depressing a pushbutton on a timer. After 2½ min, when the timer cycle is completed, the tail valve closes and the wing valve re-opens.

Engine inlet guide vanes and the accessory cover (bullet) are heated with 8th-stage air. The cowl leading edge is heated with 13th-stage air. Both the 8th- and 13th-stage airflows are controlled by thermostatic valves. Air to the cowl is reduced in temperature by mixing double skin-exhaust air with the 13th-stage air in a jet pump. Methods for removal of rain from the windshields were evaluated, and electrically actuated high-speed windshield wipers were chosen in conjunction with a liquid rain repellent.

Modifications for Series 30

The airflow into the Series 30 turbine can take two paths through the nozzle, since operation of the nozzle area is controlled by an on-off valve. APU operation on the ground utilizes the smallest open area by closing the turbine inlet valve. The entire nozzle area is available (valve open) for operation from engine bleed. In addition, the flow-control valve setting was increased approximately 25% and the air conditioning pressure-regulator setting raised to a nominal value of 27 psig.

Although the wing leading edge incorporates a full-span slat, the Series 10 type of anti-icing system was retained. A single telescoping duct connection per wing, which articulates and extends, accommodates the slat extension by carrying the anti-icing air across the slat gap. No heat is supplied to the fixed wing behind the slat. Air is discharged from the slat inner surface to the slat gap. With the slat retracted, a seal in the gap forces the discharge air to leave the gap across the wing lower surface.

Considerations and Design Innovations

Bleed air source

Four different bleed air sources are provided on each engine, i.e., fan, 6th stage, 8th stage, and 13th stage. The characteristics of each were evaluated carefully with the air conditioning and ice protection needs in mind. By proper switching it was possible to limit the needed bleed source to only two (8th stage and 13th stage) and still to avoid the use of air in the air conditioning system which had been heated to temperatures at which toxic oxidation products might exist in the event of an engine bearing seal failure. The addition of the 330 and 550°F switches to limit further the action of the 18½-psig regulator (augmentation valve) during the air conditioning mode of operation was made only after careful evaluation of the in-flight temperatures as calculated from the engine manufacturer's data. This evaluation indicated that, with the change in bleed source controlled by gage pressure alone, air that had been heated above the established limit in passage through the compressor would enter the air conditioning system during a considerable portion of the long-range cruise envelope. The 550°F switch was added to limit the temperature when 13th-stage air is in use by switching to 8th stage. Addition of the 330°F switch in the 8th-stage supply was made in order to signal that the 8th-stage air in use is sufficiently low in temperature that a change to 13th can be made and yet not encounter 13th-stage temperatures in excess of 550°F.

Through the switching means employed, it has been possible to eliminate the need for a bleed air pre-cooler and to accomplish all the needed temperature reductions through the air-conditioning heat exchanger and associated equipment. Further, 8th-stage air is utilized to the maximum extent possible with its inherent savings in aircraft performance penalty when compared with 13th-stage air usage.

1. **Augmentation valve**
2. **Crossfeed valve**
3. **Ice protection pressure regulator**
4. **Tail ice protection shutoff valve**
5. **Wing ice protection shutoff valve**
6. **Cowl anti-ice shutoff valve**
7. **Cowl anti-ice thermostatic control valve**

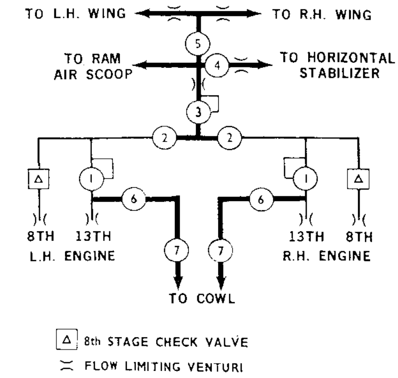


Fig. 5 Ice protection system schematic.

Pneumatic component locations

Previous experience had indicated that the extreme environment surrounding the engine contributed to both poor service and poor performance of pneumatic components. As a result, considerable effort was spent to locate all possible components remote from the engine. Except for the engine inlet ice protection valves and the 8th-stage check valve, all components are located in the tail compartment, as shown in Fig. 2, where easy access exists for service activities.

Pneumatic system duct design

All ducting upstream of the air-conditioning system pressure regulator and the ice protection shutoff valve has been designed to accept maximum 13th-stage bleed conditions. This approach eliminated the need for a relief valve to protect the duct system against a failed open augmentation valve. Though duct failures are not expected, compartments through which pneumatic ducting pass are provided with blowout panels for pressure relief at a pressure sufficiently low that structural damage does not occur. In the tail compartment no additional blowout protection is required since the louvred area shown in Fig. 6 provides for the entry of heat-exchanger fan cooling air and is sufficient to limit tail compartment pressure to a safe value in the event of duct failure. An over-temperature sensor is installed in the tail compartment as well, in order to warn the crew should temperatures higher than normal exist.

Bleed air dirt elimination

The 8th-stage air extraction point consists of an annulus around the periphery of the compressor. Unfortunately, dirt entering the compressor inlet is centrifuged to the case and concentrated in the layer of air extracted through this annulus. Previous service experience had indicated considerable damage would result to components through which this dirt-ladened air was routed. Since the majority of the dirt

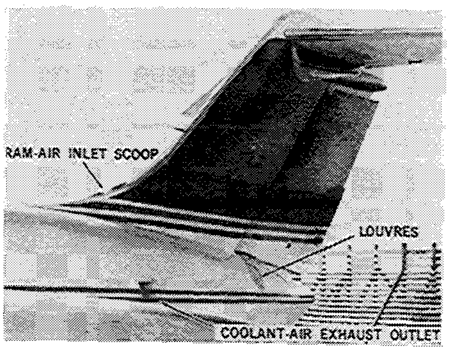


Fig. 6 Coolant air inlets and exhaust.

was found to enter the engine during thrust reversal, the air conditioning system controls were designed to shut down the system during this phase of operation. Initial flight testing, however, indicated that these precautions were insufficient to eliminate the dirt problem completely. Filters require considerable space and are quite heavy, so another method was considered. Thirteenth-stage air is extracted through a strut in the main compressor airstream remote from the compressor wall and, since tests showed this air to be considerably freer of dirt than the 8th-stage air, it could be used during reverse thrust to pressurize the ducting downstream of the 8th-stage check valve yet upstream of the closed air conditioning and ice protection system shutoff valves. A small portion of 13th-stage air would also be discharged into the 8th-stage collector in sufficient quantity to prevent air from entering the collector during acceleration at reverse thrust. Indications to date are that this approach has proved to be very effective and a filter will not be needed. A schematic of this method is shown in Fig. 7.

Rapid airflow response

Since engine accelerations and decelerations can cause sudden changes in pressure available, rapid response to changing conditions must be provided to avoid undesirable variations in in-flow to the cabin. To provide this rapid response, pneumatic actuation of the 13th-stage valve was selected, and rapid response temperature sensors were installed to signal valve actuation.

Air conditioning airflow control

In an effort to keep it simple yet provide adequate refrigeration, the air conditioning regulator was chosen to be a simple regulator with a pressure setting only slightly above bleed air pressure available at 13th stage during idle. This approach minimizes the influence of engine power setting on airflow through the air conditioning system, and eases the cabin pressure control duties as well. The flow control valve operates to maintain a fixed differential between upstream and throat pressure of a venturi. Flow variations resulting from altitude effects on density of the air through the valve were judged acceptable in preference to complicating the control for altitude compensation.

Refrigeration system heat exchangers

The bleed air switching arrangement permitted the use of aluminum heat exchangers in the air conditioning system. By limiting the temperatures that the heat exchanger would experience to 600°F, it was possible to lower the stress level sufficiently so that the aluminum headers could be utilized and the heat-exchanger construction could be simplified greatly. Again, past experience had indicated the need for careful attention to heat-exchanger thermal stresses for those heat exchangers experiencing sudden temperature changes associated with handling air from a jet engine. Temperatures and pressures associated with the conditions of sudden power application at takeoff, as well as for startup with the APU, were applied to the heat exchanger during laboratory development, and design changes were made as necessary to eliminate failures resulting from thermal cycling.

To ease installation and removal of the heat exchangers, a special connector was designed for attachment of the cooling air ducts to the heat exchanger. By loosening a bolt in each of the four corners, this device can be telescoped into the cooling air duct, permitting removal of the heat exchange without disturbing the cooling air ducting. Since the heat exchanger cooling air faces are approximately 8 in. × 23 in., such a device has eliminated the need for a considerable number of bolts for the conventional bolted flange connection.

Heat-exchanger coolant air circuit

Cooling air enters during flight through a scoop in the vertical stabilizer shown in Fig. 6 and travels through a sharp bend before contacting the heat-exchanger face. This location, plus the sharp turn, minimizes foreign-object damage to the heat-exchanger inlet face for improved service life. A review of the cooling requirements and the drag associated with cooling airflow indicated that the simplicity associated with a fixed exhaust outlet overshadowed the aircraft performance penalty, and a fixed exhaust was used. The cooling air fans for ground operation extract air from the tail compartment through louvres previously mentioned as structural protection devices in the remote event of a pneumatic duct failure. In this way, ducting is minimized, and ease of installation and removal of the fan is provided. The selector valve, which closes off the unused cooling air supply source, is air-operated to eliminate the need for an actuator with its potential service problems.

Refrigeration unit

A search for a refrigeration unit of reliability proven through service experience uncovered a bootstrap air cycle machine that could provide the needed reliable refrigeration with little modification. Previous experience with this unit had uncovered service problems resulting from the dirt-contaminating 8th-stage bleed, the accumulation of water in the oil sump, and the accumulation of ice on the turbine exducer. Corrections were made for all known difficulties. To protect the rotating equipment from damage resulting from operation during loss of cooling airflow across the primary or secondary heat exchanger, an over-temperature switch was installed at the compressor discharge and at the turbine inlet.

The bleed air control design allows the regulator and flow-control valve to remain open without electrical power so as to avoid loss of pressurization during flight in the event of electrical power failure. As a result, it was possible to apply pneumatic power to the aircraft on the ground when elec-

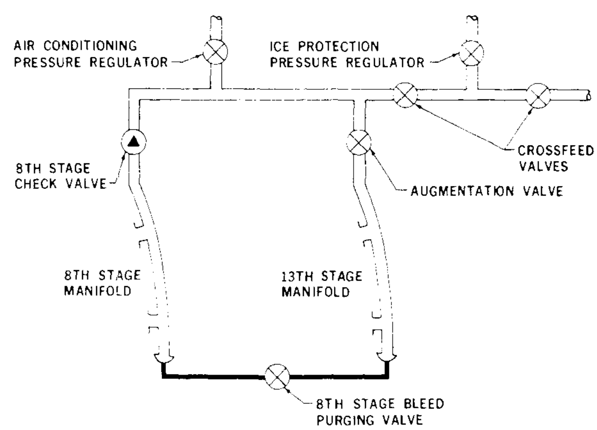


Fig. 7 Bleed air dirt elimination schematic.

trical power was not available to operate the cooling air fans, and hot bleed air would flow uncooled into the bootstrap machine. Without a protective device, the uncooled air causes considerable damage to the refrigeration equipment and, in extreme cases, could cause damage to the ducting and cabin interior as well. In order to guard against this damage, a pneumatic switch was added to the flow-control valve to prevent this valve from opening in the event of insufficient heat exchanger coolant airflow.

Water separation/freeze control devices

A review of service experience with water separation devices indicated that problems in this category have been general with all previous aircraft, and it appeared that the DC-9 deserved a careful review of means to prevent freezing in the separator. Early separators had used fiberglass cloth for the coalescer bag. The fragile glass fibers fractured in service and accumulated in the water drain line to eventually plug the drain. This shortcoming was overcome by substituting Orlon felt cloth for the fiber glass. The method used for temperature control, as shown schematically in Fig. 8, combines the desirable features of previous temperature-control systems. The screen control has proved effective before, but under some operating conditions screen icing results in a severe reduction in airflow. The addition of a valve to add warm air from the discharge of the primary heat exchanger restores the airflow and controls the screen to a condition of incipient icing.

By including a thermostat in the control line for the valve, opening of the valve is prevented with water separator temperatures above approximately 40°F, assuring maximum refrigeration. Below this temperature, the thermostat vents the control line to ambient, permitting the valve to open with an increase in differential pressure between turbine discharge and ambient resulting from either ice formation on the screen or an increase in cabin pressure differential. Sufficient differential pressure and turbine cooling capacity exist at altitudes above approximately 15,000 ft such that the valve opens regardless of screen ice, and provides a combined airflow through both the turbine and valve to assure cabin pressure control in the event of one air-conditioning system failure, an engine power reduction for descent, and a simultaneous request for maximum refrigeration.

Valve instability previously encountered with pneumatic water separator temperature-control systems is reduced to an acceptable level by highly damping the valve with silicone fluid. A large stroke in a short temperature range for a sharp control point for the thermostat is assured by using an eutectic wax actuator. This actuator (Vernatherm) previously had proved to be highly successful during service as a control for engine fuel heaters. A bonus received with the all-pneumatic control is the independence from electrical power and the associated need for an electronic control to hold a constant separator inlet temperature. In addition, sealing the wax in a tubular case eliminates the source of previous problems caused by exposing fragile thermistors to a wet airstream. An added bonus with the screen control is the more rapid pulldown of cabin temperature during low-humidity, hot-weather conditions when ice will not appear at the screen until the turbine discharge temperature reaches the dewpoint.

Air conditioning shutdown with engine failure

An increase in second segment limiting aircraft weight and a reduction in takeoff field length can be realized if bleed airflow for air conditioning is not used after an engine failure during takeoff. To require that the air conditioning systems be shut down prior to each takeoff would have increased crew workload, compromised comfort, and presented a cabin pressure control problem after each takeoff. The performance improvement is realized without the undesirable side effects by installing an automatic shutdown feature to shut off both air conditioning systems in the event of an engine failure at takeoff. This is accomplished with two different pressure switches that compare 13th-stage pressures. If a differential in excess of 70 psig exists, both air conditioning systems are shut down automatically. A manual switch is installed in order to deactivate this feature after takeoff, and thus avoid the loss of cabin pressure should an engine fail in flight.

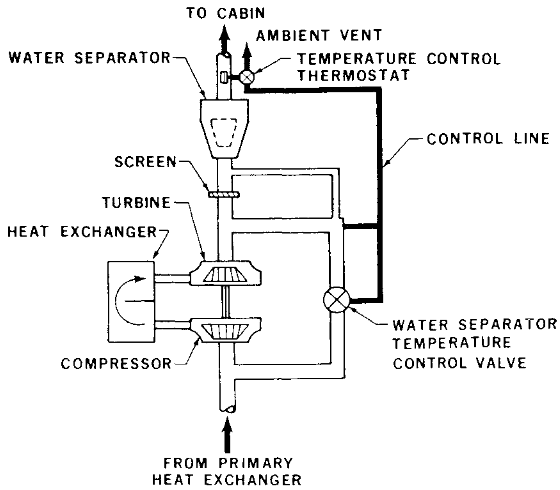


Fig. 8 Water separator temperature-control schematic.

Component interchangeability

As an aid to the logistics for the airplane, all the operating components except the cooling air selector valves are completely interchangeable from the left- to the right-hand system. On the Series 10 airplane the primary and secondary heat exchangers for each system are interchangeable with each other as well.

Performance monitoring

For the purpose of monitoring operation and troubleshooting, the pressure existing between the pressure regulator and the flow-control valve, as well as the pressure between crossfeed valves, is transmitted to indicators in the cockpit. Air delivery temperature indication from each air conditioning system is made available in the cockpit, and an annunciator light illuminates in the event the bleed air supplied exceeds an established value.

Cabin/cockpit temperature controls

The solid-state, electronic, temperature-control system for the occupied areas is practically identical to a system already proved capable and reliable in service. Only those modifications were made which were necessary to make the system compatible with the new airplane. In addition, a very small amount of air from a point downstream of the air conditioning pressure regulator was utilized for primary air in a jet pump to aspirate a flow of cabin air across the automatic control sensor and the sensor for the remote indicator in the cockpit. This approach provided a rapid temperature-control response with no moving parts, and required only a small cabin airflow rate, thereby minimizing tobacco-tar accumulation.

All the units in the cabin and cockpit temperature-control systems are interchangeable between systems, except for the anticipators in the air supply duct. Since these are matched to the time constants of the particular system, the cockpit element must be different from the cabin element. Threads in the mounting boss and electrical connector shells are different between elements to prevent improper installation. This is true of all sensors in the environmental control systems where

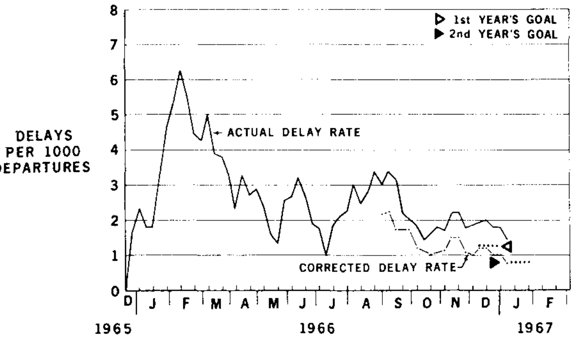


Fig. 9 Trip departure delays, DC-9 environmental control system (4-week moving average).

interconnection is possible or installation at the wrong location is undesirable.

A portion of the fuselage was assembled in the Douglas climatic chamber in order to develop an air distribution system that accomplished good temperature distribution yet caused no objectionable drafts across the occupants. In order to permit the crew to select conditions best suiting the individual, five adjustable, conditioned-air inlets are installed in the cockpit addition to the two continuous flow inlets located near the rudder pedals. Four of these five inlets are fully adjustable as to airflow rate (full-on to full-off) and adjustable as to orientation as well.

In the event of failure of the automatic temperature-control system, the temperature-control valve can be repositioned by manual application of electrical power to the actuator. The temperature of the air supplied to the cabin from each air conditioning system can be read in the cockpit. This aids in the use of manual control and also aids in troubleshooting. Temperature-control valve position is also transmitted to the cockpit to aid in monitoring and troubleshooting.

In order to improve the environment in which the flight instruments were required to operate, special cockpit exhaust air paths were provided in order to move air behind the instrument panels. The increased use of solid-state devices in the electronic equipment eased the cooling requirements for temperature control of the navigation and communication equipment. Internal air circulation through the equipment, with the associated dirt and tobacco-tar accumulation, was no longer needed. Thus, the cooling requirement of the radio rack was reduced to that of only providing good circulation of the cockpit exhaust air through the electrical compartments.

To avoid adding the complication of automatic temperature control for the lower cargo compartments, the radio rack exhaust air is routed under the forward cargo compartment floor to provide animal-carrying capabilities in this compartment. The limited heat rejection by the solid-state equipment required special precautions to be taken to insulate cold structure in the tunnels. The aft cargo compartment is kept above freezing by baffling of the aft right-hand tunnel to force the cabin air exhausting into that tunnel to flow under the floor to reach the cabin air outflow valve in the left-hand tunnel. This design approach eliminated the need for a fan with its inherent service requirements.

Cabin pressure control

A review of the service problems encountered with cabin pressure control highlighted a need to provide an outflow valve actuating force independent of cabin differential pressure so that resistance to valve movement associated with dirt or tobacco-tar accumulation could be overcome at liftoff. For this reason, an electrical actuator was chosen. The successful pneumatic controller was combined with an electronic amplifier so as to position the electrically actuated outflow valve. The lever-actuated, cable manual control of the outflow valve directly was chosen as the ultimate in reliability, permitting dispatch regardless of the type of automatic system malfunction. Reliability of the outflow valve and its manual control had already been proved during millions of hours of successful DC-8 operation. The valve's large open area essentially eliminates any cabin pressure bump when the cabin door or cockpit window are closed on the ground, even with full air conditioning airflow supplied simultaneously. Through wind-tunnel tests, the nozzle portion of the outflow valve was developed to recover approximately 1% of the engine thrust during cruise.

Ice protection system design

In light of the goal established to "keep it simple," the use of thermal anti-icing for the critical heated areas appeared to be most desirable, with engine bleed air the most reliable and straightforward source of heat. Since the ice protection system must be operable from one heat source, the total air quantity being bled during single-engine operation must remain within the limits established by the engine manufacturer. The combined requirements for wing and horizontal stabilizer anti-icing in addition to the air conditioning airflow would have exceeded the established bleed limits. Since elevator effectiveness during landing with an airplane center of gravity at the forward limit dictated the need for a comparatively clean horizontal stabilizer during this phase of flight, protection from leading-edge ice was required. The simplest possible compromise resulted in wing anti-ice with manually initiated tail de-icing. Components with moving parts were installed in easily accessible locations in order to permit rapid replacement in the event of malfunction.

Air conditioning the Series 30

The decision to proceed with the DC-9 Series 30, a larger version of the airplane, forced design changes to be made in the basic DC-9 air conditioning systems. The increased number of passengers not only required an increase in airflow to maintain the ventilation rate per passenger, but also necessitated an increase in refrigeration at the lower flight altitudes. These requirements caused the regulator setting to be increased, the flow-control valve characteristic to be changed, a larger secondary heat exchanger to be installed, and the nozzle area of the refrigeration turbine to be increased. The large nozzle area was incompatible with the APU capability. Since as high a ventilation rate as possible was desired from the APU, and the flow available exceeded the flow requirements of the only air-conditioning system, it was decided to split the flow between the two systems. In order to obtain maximum refrigeration on a hot day from the less-than-rated flow through the turbine, it was necessary to make a reduced nozzle area available during ground operation with the APU. The area reduction is accomplished by selecting the shutoff valve closed in one of two ducts between the secondary heat exchanger and one row of a two-row turbine nozzle. With the turbine nozzle shutoff valve closed in each of the air conditioning systems, and maximum refrigeration requested on a 90°F day, the supply pressure increases to very nearly the regulated value from the APU, and the minimum turbine discharge temperature is attained commensurate with this pressure ratio.

IV. First Year's Service Experiences

Data from the first year's service experiences indicate the high degree of reliability of the DC-9 environmental control systems and of the DC-9 as a whole. Delta Airlines commented in Ref. 1 that "The DC-9 is the most reliable new airplane that we have ever had." Passenger load factors on Delta's flights have been higher than predicted, and their utilization rate of 9 hr/day exceeds their goal by 1 hr/day. The fleet daily utilization average for airplanes of United States registry is 7.5 hr.

The first scheduled DC-9 revenue flight occurred on December 8, 1965. By the end of the first year, 66 aircraft in service with 14 airlines had accumulated 82,943 flight hours, of which 67,338 were revenue hours. The average flight duration was 0.75 hr. In achieving a low departure-delay rate, it was necessary to provide corrective action for service difficulties encountered in spite of the care taken in the original design.

Trip Departure Delays

Emphasis is placed on delay rate as an indication of system reliability. Figure 9 is a plot of the trip departure delays for the DC-9 environmental control systems for the first year's operation. All delays attributed to environmental control systems are counted if they exceeded 1 min. The delays are plotted as a 4-week moving average to smooth out the curve. The environmental control system in this plot includes pneumatics, air conditioning, cabin pressurization, airframe ice protection, oxygen systems, and all associated cockpit displays. Also shown is a plot of the corrected delay rate, which is derived by first removing all delays considered to be of an operational nature and by deducting 80% of the delays for which corrective service changes have been made available to the airlines but had not yet been incorporated into the airplane. The 80% factor is the predicted effectiveness of the corrective action taken based upon the Engineering Reliability Group statistics. The out-of-phase relationship between the two curves results from the time involved in supplying parts and information to the airlines plus the airline maintenance activity associated with planning and accomplishing the work. As an example, although eight cabin pressure-control system service bulletins recommending airline action are in process, only 33% of the airplanes have been modified.

It can be seen from Fig. 9 that there is a definite downward trend in delay rate. The initial peak resulted from having few airplanes in service and encountering six delays in 2 weeks, two of which were attributed to unfilled crew oxygen cylinders. Problems with temperature sensors, with water in the cabin distribution ducting, and with cabin pressure control were experienced in the first year. (A discussion of these problems is presented later in this paper.) The reduced delay rate between January and June was the result of a very concentrated effort which eliminated the water in the cabin ducting and corrected some of the pressure control faults. The low point in July occurred just prior to the airline strike. A sudden increase in the failure rate of a solenoid in a cabin pressure control component contributed to the increase in delays in the period following the strike.

Delay Reduction Program

The delay deduction program involves company-wide concentration for solving delay producing problems. Each morning, a meeting is held within Engineering to review the previous day's delays as reported by Douglas service representatives stationed with each airline. Also reviewed are customer items and field service reports. The accelerated program of corrective action is called "Solution to Customer Aircraft Troubles" (SCAT). If an item is identified as SCAT, all affected functions at Douglas and at the vendor place first priority on accelerating design improvements. Engineering changes are incorporated on the production line at the earliest possible effectivity while simultaneously making service changes available to the airlines.

To illustrate more fully the problems associated with delay reduction, an analysis was made of the delays that occurred in the month of December 1966, one year after the DC-9 went into revenue service. In this month, there were 31 delays out of 16,649 departures, or 1.9 delays per 1000 departures charged to the environmental control systems. Of the 31 delays, 14 were caused by mechanical deficiencies for which corrective action had been taken on the production line and service changes had been made available to the airlines, but had not yet been incorporated. Six delays were caused by improper operating procedures (empty oxygen cylinder, mechanism out of rig, etc.) or damage caused by personnel (coffee spilled on an oxygen regulator, damaged duct, etc.). By assuming that all the service changes had been incorporated and by eliminating any improper airline operating procedure, only 11 incidents remained, representing 0.7 delay per 1000 departures, for which corrective action could be taken. Of the 11 incidents, seven were completely unrelated. The preceding summary of one month's delay incidents illustrates the effectiveness of the delay reduction program and also illustrates the difficulty that is being encountered to reduce delays further.

Examples of Service Difficulties

As might be expected with a new product, there were a few problem areas that required design improvement. Examples are discussed below.

Cabin pressure control

The cabin pressure control outflow valve installed on the DC-9 is identical to the unit that has given extremely reliable service on the DC-8 since 1958. The cable system, including the lever and locking device, is also identical in the two airplanes. Incorporation of this portion of the cabin pressurization system should have resulted in reliable operation of the DC-9 at the outset; however, initial development and service problems were incurred. A switch, actuated by the manual lever on the pedestal to transfer control from automatic to manual and vice versa, would not provide reliable transfer. This resulted from a lack of lubrication of a spring-loader plunger and an improperly adjusted transfer switch. Difficulty was also experienced with interference of the outflow nozzle with its housing, which caused instability of the automatic system. In addition, the actuator, which was new because of the new automatic control system, would not declutch because of an internal interference. By making component changes, by sending service letters with detailed lubrication and rigging instructions, and by dispatching a team of engineers and service department representatives to assist the airlines, delays associated with the cabin pressure control system have now been significantly reduced.

Temperature-control sensors

Eight identical temperature sensors are installed in the ducting for various warning light and system control applications in the pneumatic and ice protection systems. Although a simple state-of-the-art sensor was chosen, there have been failures in all installed positions. The failures are attributed to airborne high-frequency vibrations in the acoustic range within the ducting, and a strengthened redesign of the sensor itself solved the failure problem, except for four particular locations.

Sensors in two of the four critical positions, the 330°F bleed air source control sensors, were deleted as were the 550°F sensors. These deletions were made possible by the receipt of revised engine bleed air data from the engine manufacturer which revealed the 13th-stage bleed air temperatures to be significantly lower than originally stated. With these reduced temperatures, the portion of the DC-9 flight envelope during which bleed air temperatures are above 550°F is practically nonexistent. Switchover control between bleed ports now occurs as a result of gage pressure alone. In the event of operation in the critical flight conditions, the over-temperature light will illuminate. Selecting the instrument panel switch position to "high bleed off" will return operation to use of 8th stage until a lower engine power setting is applied and the switch position returned to "auto."

Deletion of the 550°F sensors vacated a desirable location for the other two critical sensors—those that are used for the air conditioning, air supply, over-temperature warning lights. This relocation was accomplished. Thus, not only was a high failure-rate condition eliminated, but system simplification was also realized.

Water and ice in the cabin air distribution system

Occasionally during flight test and frequently during the early stages of service with the airlines, water and ice were reported in the overhead air distribution ducting. Ice could be heard tumbling inside the duct, water that had left the duct through hose connections dripped onto passengers, and water would discharge from the forward cabin and cockpit overhead supply air grilles.

A review of flight test data revealed that the water on the coalescer bag would freeze as a result of a sudden depression in turbine discharge temperature early in the climb. This temperature drop could be duplicated during flight test by a throttle reduction followed by a sudden power advance. The increased pressure drop associated with the iced separator bag caused the separator relief valve to open and to transfer freeze control functions from the screen to the bag. Because of the rapid airplane rate of climb, the air temperature available from the primary heat exchanger to the control valve was soon below freezing and the ice remained. During flight the ice so formed would break off in random pieces and rumble down the duct. Small ice crystals passing through the open relief valve changed to liquid upon mixing with the controlled flow of hot air prior to distribution in the occupied areas. Water separator effectiveness would not be regained until the airplane returned to warmer ambients and the bag thawed.

The problem was solved by adding a small duct to supply a portion of the control valve discharge air to the inlet of the water separator downstream of the screen. This raised the separator temperature a few degrees above the screen temperature any time the valve was open. The warmer separator bag now accepts the sudden temperature transients without the bag freezing.

Water dripping onto passengers in the ventral stair

Water removed by the water separators was piped overboard via the heat-exchanger coolant air exhaust which is located above each engine pylon. This proved to be a satisfactory arrangement until the first rear loading ventral stair airplane went into service with Hawaiian Airlines. With the heat-exchanger coolant air fans operating on the ground, the water mixed with the discharge overflow and "rained" on the passengers around the rear of the airplane. In addition, some of the water collected on the exhaust duct wall and ran out the outlet, down the fuselage skin to the pylon, along the pylon to the trailing edge, and then down the fuselage skin to the stair door jamb from where it dripped onto the loading passengers.

The water outlet was then relocated to a flush outlet in the fuselage skin just forward of the ventral stair. The stair protected the passengers from the dripping; however, this created another problem in flight. Because the outlet was located in a positive-pressure area, the water would flow aft along the skin to a door crack and up into the tail section where it accumulated. At landing, the heat exchanger coolant air fans created a negative pressure in the tail section which kept the water from draining until the ventral stair door was opened; the water again dripped onto the passengers below. The run-back of the drain water along the fuselage skin was finally prevented by extending the drain pipe 2 in. into the boundary layer.

V. Concluding Remarks

The DC-9 environmental control system has been designed to provide the comfort and safety expected of a modern jet airplane, yet possesses high reliability, ease of maintenance, and a high degree of dispatchability required for a large percentage of on-time departures. The first year's service has demonstrated guaranteed performance, though not without some service difficulties. Through an organized, concentrated effort, these difficulties have been corrected to permit achievement of dispatch reliability 17% below the first year's goal of 1.2 delays per 1000 departures.

It is believed that the successful operation obtained can be attributed directly to system simplicity. Considering the number of components comprising air-using systems as a measure of the degree of system simplicity attained, the DC-9 has 20% fewer parts than a competitive jet aircraft and 40% fewer parts than a contemporary four-engine jet aircraft. The delay goal has been reduced to 0.90 delay per 1000 departures for the environmental control system in its second year of airline service as evidence of a continuing effort to improve dispatch reliability.

Reference

[1] Brown, D. A., "Introduction of DC-9's Smooth for Delta," *Aviation Week and Space Technology*, Vol. 85, No. 11, Sept. 12, 1966, pp. 42–47.