AEROSPACE INFORMATION REPORT

AIR1609™ REV. A

Issued 1982-04
Revised 2005-03
Reaffirmed 2015-11

Superseding AIR1609

(R) Aircraft Humidification

RATIONALE

AIR1609A has been reaffirmed to comply with the SAE five-year review policy.

TABLE OF CONTENTS

1. SCOPE:

This SAE Aerospace Information Report (AIR) covers the design parameters for various methods of humidification applicable to aircraft, the physiological aspects of low humidities, the possible benefits of controlling cabin humidity, the penalties associated with humidification, and the problems which must be solved for practical aircraft humidification systems. The design information is applicable to commercial and military aircraft. The physiological aspects cover all aircraft environmental control applications.

1.1 Purpose:

The purpose of this AIR is to provide guidelines for the design of aircraft humidification systems. Physiological effects of humidity levels on crew and passengers are reviewed. Various techniques used for cabin humidification are discussed and evaluated. Various technical issues are addressed, and effects associated with humidification systems are described.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

2.1.1.1 ARP987 The Control of Excess Humidity in Avionics Cooling

2.1.1.2 AIR1204 Control of Water Carryover from the Environmental Control System and Condensation on the Structure

2.1.1.3 AIR1168/3 Aerospace Applied Thermodynamics Manual, Section 3, Aerothermodynamic Systems Engineering and Design

2.1.2 Government Publications: Available from Superintendent of Documents, P.O. Box 371954, Pittsburgh, PA 15250-7954.

2.1.2.1 Food and Drug Administration Public Health Service Publication No. 308, Handbook on Sanitation of Airlines

2.2 Other Publications:

2.2.1 D. A. McIntyre; Indoor Climate, Applied Science, 1980.

2.2.2 L. B. Anderson MD, Gunnar R. Lundquist MSC, Preben L. Jensen, Donald F. Proctor MD; Human Response to 78 Hour Exposure to Dry Air, Arch. Environmental Health, Vol. 29, December, 1974.

2.2.3 ASHRAE Handbook, Fundamentals Volume, 1997.

2.2.4 W. F. Storm, et al; Effect of Low Humidity on Human Performance, USAF School of Aerospace Medicine, Brooks AFB, Texas. SAM-TR-73-3, Feb 1973.

2.2.5 J. R. Dille MD; Further Information Concerning Humidity Control for Air Crew Performance. FAA-CAMI Oklahoma City, OK. File AC-100 Oct 1970.

2.2.6 E. W. Dunklin and T. T. Puck; The Lethal Effect of Relative Humidity on Airborne Bacteria. Journal of Experimental Medicine 87:87, Feb 1948.

2.2.7 W. H. Carrier: Rational Psychrometric Formulae, Transactions A.S.M.E., 1911.

2.3 Nomenclature:

This list contains symbols used in equations, charts and descriptions in this AIR.

G Water added to increase humidity, kg/min (lb/min)

m_p Average moisture generated per passenger, kg/min (lb/min)

m_c Average moisture generated per crew member, kg/min (lb/min)

n_p Number of passengers

n_c Number of crew members

P_c Cabin pressure, kPa absolute (psia)

P_v Saturated vapor pressure of water at the dry bulb temperature, kPa absolute (psia)

RH Relative humidity, %

W_a Outside air flow rate into the cabin, kg/s (lb/min)

W_r Recirculated air, kg/s (lb/min)

2.3 (Continued):

x Ratio of moisture in recirculated air to moisture in cabin air

ω_a Specific humidity, ambient, kg/kg (lb/lb) of dry air

ω_c Specific humidity, cabin, kg/kg (lb/lb) of dry air

ω_s Water vapor at saturation at dry bulb temperature and at the cabin pressure, kg/kg (lb/lb) of dry air

gr Grain = 0.0000648 kg (7000 gr = 1 lb)

2.4 Units:

All equations in this AIR may be used with metric (SI) or English units if consistency is maintained.

3. GENERAL BACKGROUND:

World wide variations in relative humidity range from as little as 6% in desert areas to 100% when rain is falling or the temperature is equal to or just below the dew point. The absolute (specific) humidity or water content shows an equally wide variation, being less than 2 g of water per kg of dry air (14 gr/lb) in cold winter climates to as high as 29 g/kg (200 gr/lb) during summer months in tropical areas.

The majority of people who are airline passengers live in areas where the relative humidity is between 30 to 60% most of the time. Exposure to a combination of high temperature and humidity causes almost immediate discomfort. The effect of exposure to very low levels of humidity takes considerably longer to be noticeable. Flight and cabin crews of long-range aircraft, having frequent extended-duration exposures, are among the most susceptible to the effects of low humidity, as typically aircraft humidity in cruise is often substantially lower than 30%. This is the consequence of flying at altitudes where the ambient air contains no or very little humidity. Ambient air is compressed and used to provide air conditioning inflow to the cabin.)

4. PHYSIOLOGICAL EFFECTS OF LOW HUMIDITY:

Ambient temperature and humidity affect the temperature and water balance of the human body. The inspired air is brought to body temperature and a saturated level prior to reaching the lungs by extracting heat and water from the mucosa lining the upper respiratory tract. This process cools and dries the surface mucosa. During expiration, both heat and water are recovered from the alveolar air, 37 °C (98 °F) and 100% RH as it contacts the colder mucosa of the nasopharynx. This net transfer of heat and moisture is dependent on ambient humidity and temperature.

4. (Continued):

The physiological effects of low humidity, as can be found in aircraft cabins during cruise, are unclear. There are numerous reported instances of airline passengers and crew complaining of dry noses and throats, and "gritty" eyes. The sensation of dryness of the nose is attributed to drying out of the mucosa. Most of the evidence of discomfort related to low humidity is difficult to evaluate (reference D. A. McIntyre; Indoor Climate, Applied Science, 1980). Some investigations, under carefully controlled conditions, have concluded that there is no physiological need for humidification of air (references: L. B. Anderson MD, Gunnar R. Lundquist MSC, Preben L. Jensen, Donald F. Proctor MD; Human Response to 78 Hour Exposure to Dry Air, Arch. Environmental Health, Vol. 29, December, 1974 and ASHRAE Handbook, Fundamentals Volume).

It should be noted that in cold climates, the relative humidity inside buildings can be quite low. For example, if the outside air is saturated at -6.7 °C (20 °F), the RH at 23.9 °C (75 °F) is only 11%. Many people are exposed to such humidity levels for long durations, apparently without significant adverse effects or discomfort.

4.1 Performance:

No adverse effect of low humidity on performance has been established. USAF School of Aerospace Medicine experiments showed that environments of 0.5 mm Hg (66.5 Pa) vapor pressure and/or simulated 2.44 km (8000 ft) barometric pressure (with a moisture content of about 0.6 g/kg (4 gr/lb)) had no adverse effects on performance during four 36-hour chamber exposures (reference W. F. Storm, et al; Effect of Low Humidity on Human Performance, USAF School of Aerospace Medicine, Brooks AFB, Texas. SAM-TR-73-3, Feb 1973). Department of Transportation – Federal Aviation Administration investigations have been conducted to evaluate any performance effects of low humidity. These studies concluded that the information presented with regard to humidity effects did not show that low humidity had safety implications (reference J. R. Dille MD; Further Information Concerning Humidity Control for Air Crew Performance. FAA-CAMI Oklahoma City, OK. File AC-100 Oct 1970).

4.2 Respiratory Effects:

Many medical practitioners believe that low winter humidities predispose individuals towards infection and have recommended humidification for those who suffer from respiratory troubles. The dispersal of bacterial is affected by humidity, in that bacteria are carried on small dust particles (reference W. H. Carrier: Rational Psychrometric Formulae, Transactions A.S.M.E., 1911). Increasing relative humidity encourages the particles to agglomerate, which will increase the rate at which they settle out of the atmosphere. Humidification systems may, therefore, be desirable in military airplanes used as mobile hospitals.

4.2 (Continued):

Some epidemiological investigations have been made which point to low atmospheric humidities as a factor in increasing the incidence of infection. Although these investigations support each other, none can really be considered conclusive (reference D. A. McIntyre; Indoor Climate, Applied Science, 1980).

4.3 Effective Temperature:

The effective temperature (ET*) is an index that combines into a single value the effects of dry-bulb temperature, relative humidity and air velocity on the sensation of comfort (reference ASHRAE Handbook, Fundamentals Volume, 1997). It is similar to the older effective temperature (ET) used earlier by the American Society of Heating Refrigeration and Air Conditioning Engineers, but it is based upon more current tests on effects of environment on human comfort. The index shows that as humidity is decreased, dry bulb temperature must be increased to achieve the same sensation of warmth.

4.4 Exposure Time:

Any effects of low humidity are not immediate. The incidence of passenger complaints tends to be associated with flights of 3 to 4 hours or longer, increasing with flight time. Crew discomfort is more prevalent due to their more frequent exposure to low humidity conditions. Military crews on flights lasting up to approximately 24 hours have experienced discomfort due to low humidities. Commercial flights can last up to approximately 14 hours on intercontinental routes, so commercial flight crews may experience similar effects. Frequent intake of water may reduce this discomfort.

5. HUMIDITY LEVELS IN PRESSURIZED AIRCRAFT:

The cabin and flight station humidity is a function of the ambient humidity, ventilation rate, moisture generated in the cabin and the temperature of the cabin or flight station.

The specific humidity of air in the cabin can be calculated using the general Equation 1 given below. The recirculation factor (x) is included to cover systems where recirculated air may be treated by passing through charcoal or other chemical filters, which may remove some of the moisture.

Where air recirculation is not used or where air recirculation is used without moisture removal, the denominator in Equation 1 becomes W_a.

5. (Continued):

The rate of moisture generation by passengers and crewmembers depends upon the cabin temperature, and can be determined from Figure 1. The moisture generated in galleys has not been included since it is generated intermittently and usually is vented overboard.

$$\omega_c = \frac{W_a \omega_a + [n_p m_p + n_c m_c]}{W_a + W_r (1 - x)} \qquad \text{(Eq.1)}$$

Nomenclature for this equation is found in 2.3. Note that Equation 1 assumes that no moisture is being added or removed by humidification or dehumidification systems, Equation 1 also assumes that no moisture is being removed by the air conditioning system or condensing on cold surfaces within the cabin (with the exception of moisture removal from recirculated air as noted in the second paragraph of this section).

The flight deck of transport aircraft will typically have lower humidity levels than in the cabin, due to the higher (on a per-occupant basis) air conditioning flows that are required to cool the avionics and solar heat loads. Also, the flight deck of a commercial airplane is often supplied with 100% fresh (conditioned) air, rather than a mixture of outside air and recirculated air from the cabin. In these cases, the flight deck does not benefit from any moisture generated by the passengers. The flight deck occupants generate moisture, but their contribution to compartment RH tends to be of little significance because of the aforementioned comparatively high air change rate typically found in the flight deck.

5.1 Measurement of Cabin Humidity:

Various means of measuring specific and relative humidity have been established. The following sections provide an overview of techniques applicable to aircraft.

5.1.1 Wet Bulb and Dry Bulb Temperatures: The use of these measurements is the simplest way to determine humidities and if done carefully, will yield satisfactory results.

The wet bulb measurement is critical and can only be obtained accurately when air is drawn over the temperature sensor at a high velocity. The reading then approaches the temperature of adiabatic saturation. Wet bulb temperature may be measured using a sling psychrometer or specially designed instruments that draw the air sample over dry and wet temperature sensors.

The procedure for calculation of relative humidity based on wet and dry bulb temperatures is found in Reference W. H. Carrier: Rational Psychrometric Formulae, Transactions A.S.M.E., 1911.

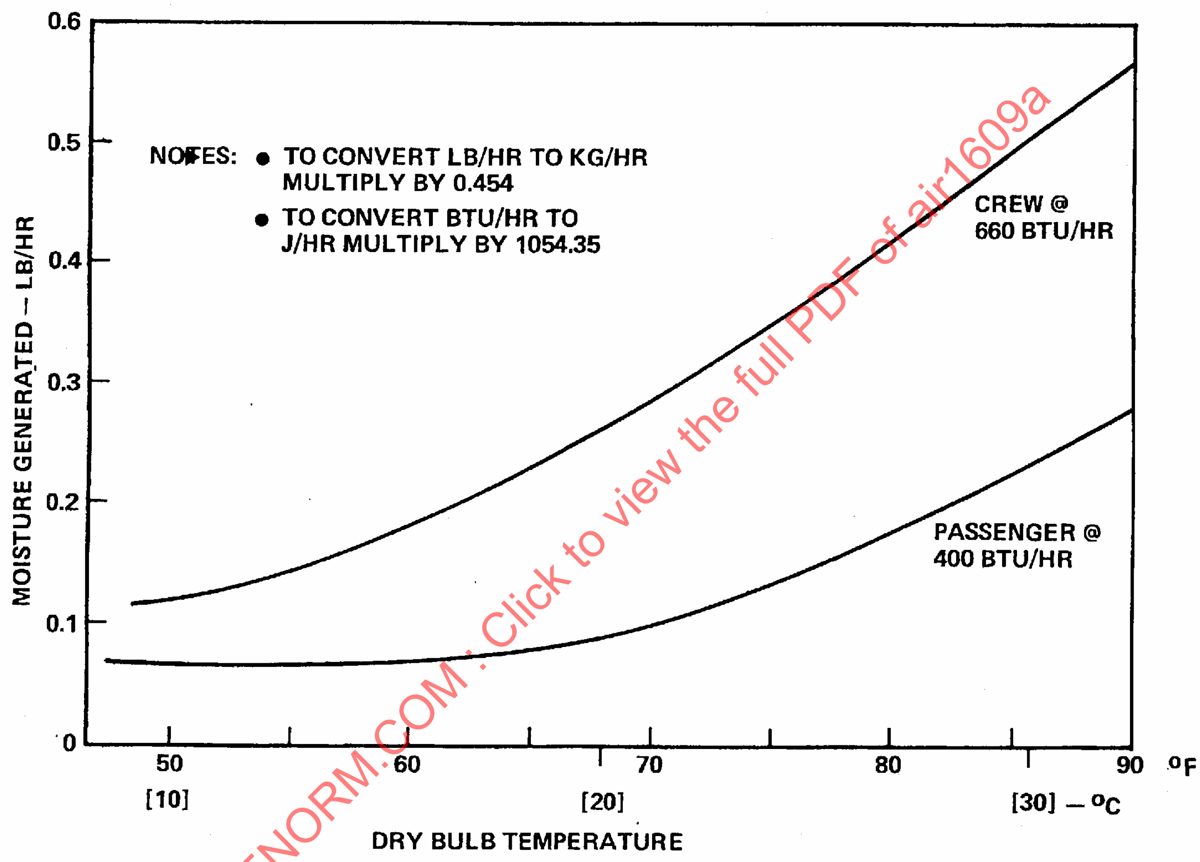

FIGURE 1 - Moisture Loss from the Average Human
(Reference 2.1.1.3)

5.1.2 Dew Point Measuring Devices: Dew point measuring devices, or “dew pointers,” are commonly used laboratory electronic instruments for measuring relative humidity. A dew pointer uses a reflective surface that is repeatedly cooled and heated in the presence of an air sample. When the surface temperature reaches the dew point of the air sample, condensation forms on the reflective surface. An optical sensor determines the presence of condensation on the reflective surface. Electronic circuitry is used to calculate relative humidity.

5.1.3 Capacitance Sensing Elements: Instruments are available which provide direct measurement of relative humidity. These instruments generally use capacitance sensing elements, which are used in conjunction with electronic circuitry to provide an electrical output as a function of absolute humidity. On-board temperature sensors are used to compute relative humidity.

6. HUMIDIFICATION IN AIRCRAFT AT HIGH ALTITUDE:

Humidification may be desirable in aircraft that cruise for long periods at high altitude. Although controlling cabin RH at 30 to 60% would optimize occupant comfort, RH levels this high can lead to unacceptable condensation at high altitudes. Inevitably at high altitude the aircraft structure of subsonic aircraft becomes so cold that the local temperature even inside the thermal insulation is low, often below the dew point. Thus, the water in the cabin air "migrates" to these cold areas and condenses.

Drainage of this condensed moisture leads to its collection in the bottom of the fuselage between the insulation or cargo floor and the skin. Since the temperatures are so low in this region, the water droplets freeze and the ice thus collected may not melt during turnaround between flights and so the water drains cannot function. Further flights lead to more condensate and ice accumulations totaling several inches thick arise. This excess and unaccounted weight could impact aircraft operation.

It has been observed that in a typical transport the onset of condensation on the windscreen pillars coincides with a relative humidity of about 30%. Taking this as a maximum and switching off humidifiers when it occurs helps to avoid an excess of condensate drainage. Taking a margin on this figure is advisable as use of the humidifier at lower altitudes where ambient moisture content may be greater may result in exceeding 30% relative humidity.

Based on the above considerations, a practical design objective for a humidification system may be to maintain of nominal 20% relative humidity with full passenger load. However, it could be possible to attain levels closer to 30% relative humidity without excessive condensation using continuous monitoring, RH sensors and active control systems.

In commercial aircraft, consideration should also be given to humidifying only small portions of the occupied volume, rather than the entire cabin. For example, the flight deck, or flight deck and crew rest stations could be supplied with humidification. This makes humidification more practical from an aircraft penalty standpoint.

6. (Continued):

In addition to active humidification, It should be noted that one means of elevating the humidity of an occupied cabin is to reduce the outside air ventilation rate; total ventilation could be maintained by correspondingly increasing the amount of recirculated air. For any given application, there are practical limits on the amount of reduction in outside air ventilation rate. These limits must consider, as a minimum, applicable regulations and air conditioning system cooling capacity.

Another means of elevating compartment humidity is in conjunction with a dehumidification system that is intended to dry the air surrounding aircraft insulation blankets on the interior of the aircraft skin. The by-product of these systems is humidified air, which is generally discharged into the cabin. The effect on a large cabin is somewhat small, albeit beneficial. These dehumidification systems are discussed in Reference 2.1.1.2.

6.1 Humidifier Input Requirements:

6.1.1 Water Requirements: The amount of water which must be added to the cabin to maintain a given water content in the air depends on the outside air ventilation rate, the moisture produced by passengers and crew, the water content of the ambient air and the desired relative humidity.

For a given relative humidity, the specific cabin humidity may be calculated by:

$$\omega_c = \frac{0.622\,P_v \cdot RH}{100\,P_c - RH \cdot P_v} \qquad \text{(Eq.2)}$$

The water that must be added to maintain a given specific humidity is:

$$G = (\omega_c - \omega_a)\,W_a - (n_p m_p + n_c m_c) \qquad \text{(Eq.3)}$$

Figure 2 illustrates the effect of outside air ventilation rate on water requirements for humidification. The ventilation rate is the total outside air supplied to the cabin divided by the actual number of passengers aboard. Thus, at low load factors, passenger ventilation rate becomes quite high unless inflow can be reduced. For one wide-bodied aircraft with a passenger load of 400 persons, the water required to maintain 20% relative humidity would be 18 kg/h (40 lb/h) or 180 kg (400 lb) over a 10-hour flight.

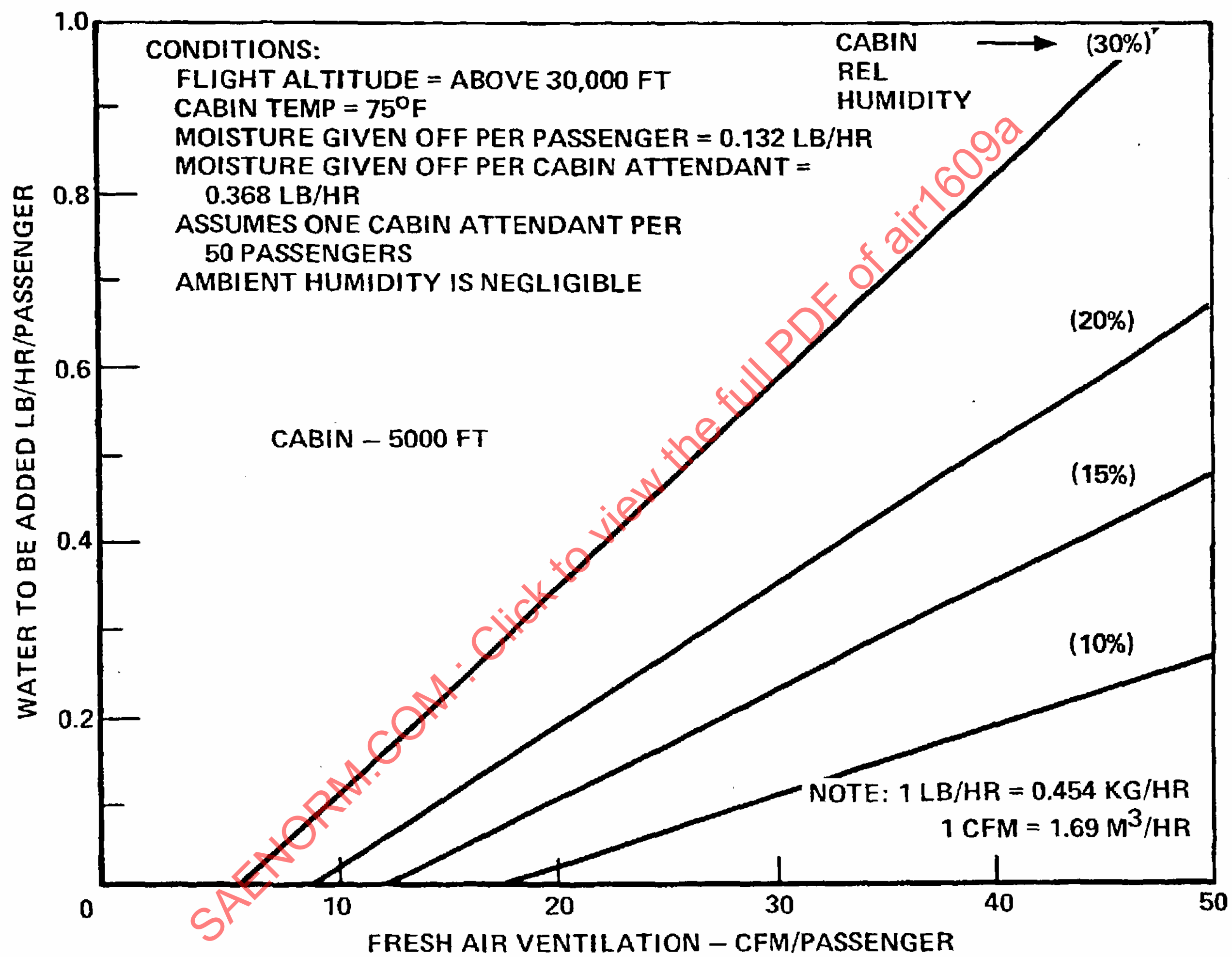

FIGURE 2 - Water Requirements for Humidification

6.1.2 Heat Requirements: Any humidification process requires liquid water to be converted to water vapor. This process requires heat, either from the aircraft conditioned air supply, or from external sources such as electrical heaters or bleed air.

If the heat energy is coming from the aircraft conditioned air supply, there will be a significant temperature depression of the humidified air. The design of the aircraft air conditioning control system must be compatible with such a temperature drop. This observation applies to the following humidifier types: spray atomizer, mechanical aerosol generator, and membrane humidifier. The vapor injection class of humidifiers do not cause any significant temperature depression of the conditioned air supply. Vapor injection humidifiers use an external heat source, and hence do not rely on heat energy contained within the conditioned air supply. If the heat energy is coming from the aircraft conditioned air supply, evaporation of the injected liquid will cause a significant depression of the humidified air.

6.2 Methods of Humidification:

A number of different techniques have been developed and utilized to humidify aircraft. This section provides an overview of the various types of aircraft humidifiers.

6.2.1 Spray Atomization: One of the simplest methods of humidification for aircraft is by means of a spray device in which a high velocity stream of air breaks up a jet of water into small droplets. The many small droplets provide a large surface area of water; thus, complete evaporation can take place provided that the air conditioning supply is not too cold.

The spray type humidifier consists of a water nozzle with an air nozzle arranged such that the axes of flow of the two fluids are at 90° to each other. With water supplied at 82.7 kPa(g) (12 psig) and air at a similar or greater pressure, a fine spray of droplets is formed.

Two units can be used; one located in one of the main distribution feeds to the passenger cabin and the other in a similar position for the flight deck. If it is possible to locate a single unit such that all areas are adequately supplied with humidified air, then a larger water orifice can be used with advantage. Simple solenoid valves switched from the flight deck control the supplies of water and air.

6.2.2 Mechanical Aerosol Generators: The aerosol generator is used in a number of aircraft humidification applications. In this system a high-speed electrical motor drives a disc that induces a flow of water over the disc. The high velocity causes the water to break up into very fine droplets. The same disc has ventilation blades that generate a moderate airflow toward the fixed vanes and evacuate the aerosol mist into the aircraft ambient air or distribution ducting.

6.2.3 Vapor Injection: Water vapor may be injected into the air distribution system to eliminate problems of non-vaporization that occur with liquid water injection. There is no buildup of contaminates in ducts or in the cabin. However, a vapor generator requires significant amounts of power to vaporize the water. In addition, the generator must handle the buildup of contaminant that will be deposited on the vaporizing surfaces.

6.2.3.1 Electric Heaters: Heaters will require about 18 kilowatts for each 27.2 kg/h (1 lb/min) of water vaporized. Heaters must be periodically cleaned. A contaminant buildup insulates the heaters, leading to higher heating element temperatures and early failure.

Another type of electric heater uses an electrode system, which heats water using the Joule effect. This works by sending a current through an immersed resistance-heating element. The heat is released by Joule effect in the resistance element. This heat isn't dissipated immediately in the fluid; a temperature difference between the heater and the water is needed to allow heat transfer. One part of the heat will increase the heater temperature, until a sufficient temperature difference is reached to cause the water to heat. In this type of humidifier, the electrodes are not subject to high temperatures, and are therefore not as prone to early failure as conventional heating elements are. If a Joule effect electrode system is employed with an active control system, this system has the advantage of adjustable vaporization power. With humidity sensors and appropriate control logic, closed-loop regulation can provide a more constant relative humidity, to compensate for changes in ambient conditions, passenger load or air flow rate.

An electric heater system should be provided with a drain system so that the concentration of dissolved contaminants does not increase to unacceptable levels. This drain system may be automated by integration with a humidifier control system. Water discharged from the humidifier can be drained to the aircraft gray water waste system.

6.2.3.2 Bleed Air: Engine bleed air, which is usually available at 120 to 200 °C (250 to 400 °F), has been used to supply the heat of vaporization. Although the contamination buildup is the same, mixing the water and bleed air in an evaporator with a large surface area for contaminant buildup can provide reasonable maintenance intervals.

In this system, water and bleed air are injected into a canister containing a large number of horizontal plates. The air-water mixture circulates over the plates where the water is vaporized. The water flow is controlled to maintain a constant discharge temperature of 65 °C (150 °F) at the exit of the canister. Bleed air flow is regulated as a function of the bleed air temperature. This provides a relatively constant amount of thermal energy and the water that is required to cool the bleed air to a fixed temperature is similarly constant. The process of mixing bleed air with water can be considered adiabatic if the canister is well insulated and can be analyzed on the basis of the air and water enthalpy.

6.2.3.2 (Continued):

Water must not be injected directly into high pressure bleed ducts unless it has been demineralized or distilled and all dissolved solids removed.

6.2.4 Membrane Humidifier: In this type of system, unheated water is circulated on one side of a semi-permeable membrane. The membrane is located in the air conditioning distribution duct, such that conditioned air flows past the other side of the membrane. On the airside, the water evaporates from the surface of the membrane, so it is supplied to the air directly as a vapor.

Like the vapor injection systems of 6.2.3, the membrane humidifier is not subject to the problems of non-vaporization that occur with liquid water atomization or aerosol generators. There is also no possibility of introducing mineral contaminants into the cabin or ducting. In addition, the membrane provides an absolute barrier to microorganisms, including viruses.

To keep the concentration of dissolved contaminants low enough so they will stay in solution, the water side of the membrane must be supplied with sufficient purge flow. This effluent stream can be drained to the aircraft gray water waste system.

6.2.5 Wicking Humidifier: This type of humidifier operates by supplying water (admitted by a solenoid valve) to an absorbent wicking element, often referred to as a pad. The conditioned air stream flows over the pad, and water evaporates from the pad. Thus, the water is delivered to the air in the vapor state, so contaminants are not introduced into the cabin or ducting. Contaminants such as microorganisms and dissolved minerals are retained in the pad. Pad life, then, is a function of the size of the pad and the amount of dissolved mineral contaminants in the water. This type of humidifier does not require a drain for normal operation, but does require drainage provisions in the event of a failure.

6.2.6 Humidity Controls: Humidity sensors and active electronics may be used to control and monitor the output of a humidifier. Manual on-off controls may also be used. It is recommended that the simplest type of control system that achieves the desired level of humidification be employed.

6.3 Humidification Problems:

The major issues in aircraft humidification are contaminant buildup, incomplete vaporization of the water, re-condensation in ducts, condensation on the interior surfaces of the airplane, and corrosion.

6.3.1 Contaminant Buildup: Potable water is normally used for humidification. Carbonates and other dissolved solids contained in the potable water build up wherever evaporation takes place.

Where atomized or aerosol liquid water is delivered into air ducts, residual contaminates, largely calcium carbonate, occur on the internal surface of the ducts. They spread through the system, and after some period of aircraft operation, begin to appear at air outlets and be introduced into the cabin as a fine dust. Valves can eventually seize and items such as temperature sensors may gradually suffer an increase in time constant, which eventually leads to malfunction of the temperature control system. Regular removal and cleaning is necessary. The deposits can be removed by dissolving in acetic acid, which must first be shown to be compatible with the material of the components affected.

Where avionics are cooled using cabin air, these salts can create a corrosion problem if they become trapped in the avionics boxes and subsequently hydrolyze. Rehydrated salts form an aqueous solution that is electrically conductive. ARP987 discusses control of humidity in avionics cooling in more detail.

It is possible to use a separate tank for the humidifier, rather than use the aircraft potable water system. This system could be filled with distilled water, thus avoiding any problems associated with dissolved mineral contamination.

6.3.2 Incomplete Vaporization: Where spray atomization, mechanical aerosol generation, or any other system which delivers liquid water in any form is used, the heat in the conditioned air stream is often inadequate for complete vaporization. In this case, water will collect in ducts and eventually leak out or spurt out through the outlets.

6.3.3 Condensation: Water condensation with increased humidity levels can be a problem, especially at relative humidities greater than 30%. Water can condense on cold surfaces, especially airplane structure. The water can wick into insulation batting. Therefore the insulation batts should be designed to be self-draining, and non-wicking. Condensed water can drip onto equipment or passengers. In the case of flight deck humidification, dripping in the flight deck can be a problem unless proper insulation and drip shielding is provided.

Unless proper insulation is provided, condensation and freezing on cold surfaces can add uncontrolled weight to the aircraft. AIR1204 discusses control of condensation on structure.

Ideally, condensation should be controlled by passive means, however, the dehumidification system mentioned in Section 6 is a possible way of addressing a condensation problem.