Aerospace Pressurization System Design

AIR1168/7

SAE Aerospace
Applied Thermodynamics Manual

Reprint

SAE *Aerospace*
An SAE International Group

AEROSPACE
INFORMATION
REPORT

SAE AIR1168/7

Issued 1991-03
Reaffirmed 2004-06

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PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the Third Edition of the SAE Aerospace Applied Thermodynamics Manual. The Manual provides a reference source for thermodynamics, aerodynamics, fluid dynamics, heat transfer, and properties of materials for the aerospace industry. Procedures and equations commonly used for aerospace applications of these technologies are included.

In the Third Edition, no attempt has been made to update material from the Second Edition nor were SI units added. However, all identified errata were corrected and incorporated and original figure numbering was retained, insofar as possible.

The SAE AC-9B Subcommittee originally created the SAE Aerospace Applied Thermodynamics Manual and, for the Third Edition, used a new format consisting of AIR1168/1 through AIR1168/10. AIR1168/11 through AIR1168/14 were created by the SAE SC-9 Committee.

The AIRs comprising the Third Edition are shown below. Applicable sections of the Second Edition are shown parenthetically in the third column.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow	(lA,1B)
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures	(1C,1D,1E)
AIR1168/3	Aerothermodynamic Systems Engineering and Design	(3A,3B,3C,3D)
AIR1168/4	Ice, Rain, Fog, and Frost Protection	(3F)

AIR1168/5	Aerothermodynamic Test Instrumentation and Measurement	(3G)
AIR1168/6	Characteristics of Equipment Components, Equipment Cooling System Design, and Temperature Control System Design	(3H,3J,3K)
AIR1168/7	Aerospace Pressurization System Design	(3E)
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning	(3I)
AIR1168/9	Thermophysical Properties of the Natural Environment, Gases, Liquids, and Solids	(2A,2B,2C,2D)
AIR1168/10	Thermophysical Characteristics of Working Fluids and Heat Transfer Fluids	(2E,2F)
AIR1168/11	Spacecraft Boost and Entry Heat Transfer	(4A,4B)
AIR1168/12	Spacecraft Thermal Balance	(4C)
AIR1168/13	Spacecraft Equipment Environmental Control	(4D)
AIR1168/14	Spacecraft Life Support Systems	(4E)

F.R. Weiner, formerly of Rockwell International and past chairman of the SAE AC-9B Subcommittee, is commended for his dedication and effort in preparing the errata lists that were used in creating the Third Edition.

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SECTION 3E - AEROSPACE PRESSURIZATION SYSTEM DESIGN

1.   INTRODUCTION

The requirements for cabin pressure for all types of aircraft have been established by the Armed Services in military specifications (Refs. 1 and 2), by the Federal Aviation Authority (Ref. 3) and by the SAE in recommendations (Ref. 4). These requirements limit the cabin altitude to 8000 ft in transport and long range military aircraft. In fighter aircraft, when the pilot uses oxygen and the mission duration is relatively brief, cabin altitudes up to 25,000 ft are allowed. Supersonic transports, which operate at high speed and high altitude, have short flight durations and high rates of descent. To avoid an uncomfortable rate of change of cabin pressure when descending from high altitudes, a maximum cabin altitude of 6000 ft is recommended in Ref. 6.

1.1   Scope

The pressurization system design considerations presented in this AIR deal with human physiological requirements, characteristics of pressurization air sources, methods of controlling cabin pressure, cabin leakage control, leakage calculation methods, and methods of emergency cabin pressure release.

1.2   Nomenclature

CA = Equivalent leakage area, in.^{2}

a_{cb} = Velocity of sound at cabin temperature, ft/sec

a_j = Velocity of sound at jet, ft/sec

F_{ex} = Exhaust thrust, lb

g = Gravitational acceleration, ft/sec^2

H = Cabin altitude, ft

M = Mach number, dimensionless

P = Pressure, in.Hg abs.

p = Pressure, lb/ft^2

P_a = Ambient pressure, in.Hg abs.

P_{cb} = Cabin pressure, in.Hg abs.

ΔP = P_{cb} - P_a, in.Hg

R = Universal gas constant, ft-lb/lb-°R

T = Temperature. °R

T_{cb} = Cabin temperature, °R

T_j = Jet temperature, °R

V = Pressurized volume, ft^3

V_{ex} = Exhaust velocity, ft/sec

w = Leakage flow, lb/min; or cabin outflow, lb/min

w_s = Cabin inflow, lb/min

W = Weight of air, lb

Z = Pressure ratio factor (defined in Par. 3), dimensionless

γ = Ratio of specific heat at constant pressure to that at constant volume, dimensionless

τ = Elapsed time, min

τ' = Elapsed time, supercritical period, min

τ'' = Elapsed time, subcritical period, sec

ρg = Air density in pressurized volume, lb/ft^3

$\Delta P/\Delta \tau$ = Rate of pressure change, in.Hg/min

1.3   Common Abbreviations

abs.   — Absolute
AC   — Alternating current
ACTR   — Air Corps Technical Report
AFSCM   — Air Force Systems Command Manual
AFTR   — Air Force Technical Report
AIR   — Aerospace Information Report(SAE)
ARP   — Aerospace Recommended Practice(SAE)
Dec.   — December
Eq.   — Equation
^{o}F   — Degrees Fahrenheit
fpm   — Feet per minute
fps   — Feet per second
ft   — feet
in.   — Inch(es)
Hg   — Mercury
lb   — Pounds
ln   — Natural logarithm to the base e
lb/in.^{2} — Pounds per square inch
min   — Minute
Par.(Pars.) — Paragraph(s)
psi   — Pounds per square inch
^{o}R   — Degrees Rankine
Ref.(Refs.) — Reference(s)
SAE   — Society Of Automotive Engineers
sec   — Second
USAF   — United States Air Force
V   — Volts
Vol.   — Volume
%   — Percent

2. PHYSIOLOGICAL REQUIREMENTS

Maximum rates of change of cabin pressure permitted in combat aircraft are relatively high, as dictated by combat emergencies. Ref. 1 specified that the pressure must be controlled within the limits of 0.5 psi/sec maximum for increasing pressure and 1.0 psi/sec for decreasing pressure. In civil and military transport aircraft, operating rates of pressure change are held below 0.5 in.Hg/min (corresponding to 500 ft/min at sea level) to minimize passenger discomfort.

2.1 Cabin Air Supply

A number of schemes are feasible for producing the required flow and pressure for cabin pressurization and ventilation; a study of the detail requirements of each aircraft will result in the appropriate means for that aircraft. Most obvious among these schemes are the following:

1. Compressor bleed from turbine engines.

2. Separate compressors driven by direct shaft from the engine compressor, by bleed turbine, by electric motor, or by hydraulic motor.

The major factors influencing the selection of the cabin air sources are:

1. Aircraft mission, configuration, and type of engines.

2. Risk of oil contamination, which can occur in using compressor bleed air from the main engines.

3. Effect of total power consumption for pressurization and air conditioning on the mission of the aircraft.

4. Reliability and safety.

5. Refrigeration and heating requirements.

2.1.1 Design Approach

The following discussion outlines the characteristics of cabin air sources.

2.1.1.1 Direct Bleed

Compressor bleed from turbine engines is attractive because of the mechanical simplicity of the system and the reliability of the source. Fuel consumption penalties due to bleeding the engines tend to be greater than those incurred when power is extracted from the engine accessory drive pad. This is because the energy contained in the engine compressor air is at a higher level than is required for the cabin, and because at rated thrust levels the effect of bleed on engine turbine inlet temperature is disproportionately higher than the energy extracted. In high performance fighters, the bleed quantity is usually small and the bleed penalty is low. Thus the bleed system may be preferred to other systems if the air is known to be sufficiently free of lubricating oil.

Turboprop transport bleed requirements are relatively high and the engine air flow low, resulting in significant fuel consumption penalties. Popular opinion regarding the risk of obtaining contaminated air from the engine may preclude its use for transport aircraft, regardless of other reasons.

Gas turbine engines with bleed ports at as many as four compressor stages allow the selection of bleed air with widely variable energy levels. Maximum fuel economy and safety are obtained by using bleed air with the lowest energy level suitable for cabin pressurization. Bleed air pressures vary widely according to engine throttle settings and flight altitudes. A typical bleed air system will extract bleed air from a higher pressure bleed port when the engine thrust settings are low, or at high altitude, and will switch to a lower pressure bleed port, for example, at higher engine settings.

2.1.1.2 Engine Shaft Driven Compressor

A directly shafted compressor can be used if the engine is equipped with a drive pad of sufficient strength to mount and drive the compressor and if the variation of pad speed with engine power can be accommodated with reasonable mechanical devices.

The speed requirements of aerodynamic compressors, axial or centrifugal flow, can be accommodated by infinitely variable ratio transmissions, multiple ratio transmissions, or even fixed ratio if the engine speed variation is small or zero. Transmissions with an infinitely variable ratio tend to be mechanically complex and expensive, and consume an appreciable amount of power in themselves. Two- or three-speed transmissions are mechanically attractive, but may require high overspeed peaks to accommodate a wide variation in engine speed.

Fixed displacement compressors such as the Roots type or the helical rotor type can be driven directly or at most may require a two-speed transmission. These machines tend to be mechanically simpler and cheaper to maintain than the aerodynamic compression machines, but their operating efficiency is somewhat lower and they are heavier. Pressure requirements can usually be met over the entire speed range, but a change in speed ratio will be necessary to obtain efficiently the required air flow schedule. Inlet throttling and discharge spilling, though not efficient, can be used for flow regulation.

The vibrational environment on the engine accessory drive pad is usually quite severe and any directly shafted accessory is likely to undergo a considerable period of mechanical development by trial and error before it becomes a reliable, long life device.

2.1.1.3 Bleed Air Drive Compressor

If in a particular installation it is not permissible to use direct compressor bleed for cabin pressurization, and a directly shafted compressor is not suitable for application, then perhaps a bleed-driven turbocompressor can be used. The air turbine drive gives the system designer flexibility of speed and air flow (independent of main engine operating conditions) and freedom of choice in locating the machines in the aircraft. Engine speed is of interest only as it affects the energy level of the bleed air that spins the turbine.

The turbine, designed to furnish sufficient power to the compressor at high altitude and minimum engine power, may not be able to operate at peak efficiency at cruising conditions. A variable nozzle turbine will suffer less loss than a throttled fixed-area-nozzle turbine, although it requires a moderate increase in mechanical complexity. The use of multiple units, installed so that one or more may be shut down when the bleed energy level is high, may be useful in further increasing the cruising efficiency of the system. Multiple units are required, in any event, to enhance the reliability of the source.

Speed controls are important for a turbocompressor that has no inherent speed limit. An over-speed shutdown control should be considered in addition to the normal topping speed governor. Further insurance against the consequences of a wheel burst will depend on the location of the turbocompressor in the aircraft and the reliability of speed limiting devices.

Turbine and compressor housings designed to contain blade fragments are required. Armor plate may be used to deflect or arrest large fragments that otherwise cannot be contained. One design allows the driving turbine to shed blades before the compressor wheel reaches a dangerous speed, thus inherently arresting further acceleration. The fatigue life of a critically designed turbine requires careful examination. Consistent tri-hub failures have been experienced, without affecting fatigue life, by designing the failure point into the hub. If the bleed air energy is reduced at the engine for safety reasons, the air consumption of the turbocompressor will be increased. However, it may not be necessary to impose this reduction during high altitude cruise operation, where the level is already much lower than at sea level, and overall operating economy may be little affected by judicious use of pressure and temperature limiters.

2.1.1.4 Hydraulic Drive

Hydraulic power for a cabin compressor drive provides speed flexibility, installation freedom, and light weight like the turbocompressor, with the added advantage of much higher drive efficiency over the entire speed spectrum. The most attractive feature of a hydraulic power transmission, which uses a piston pump and motor, is its inherently high overall efficiency over a wide relative speed range between the pump and motor. Component efficiencies of the pump and motor can be well over 90% if the losses due to fluid friction are not too great. Either the pump or the motor is a variable displacement machine, regulated by the relative speed requirements of the engine and compressor.

The use of high capacity hydraulic power transmission systems, such as this, requires a careful examination of the mechanical and hydraulic problems associated with piston pumps, motors, and interconnecting piping, which are operating at relatively high fluid flows at pressures between 2000 and 4000 psi. Though there is an inherent speed limit in the piston pump and motor system, it may exceed the safe limit of the compressor. In this case, an overspeed prevention device will be required.

2.1.1.5 Electric Drive

Electrically driven compressors for cabin pressurization are not commonly used because of generator and motor weight and inflexible speed relationships. A reasonably high voltage (100-200 V) is required to reduce the weight of the machines and wiring, and this makes necessary the use of AC power to control arcing in switch gear.

In an AC system the motor speed is a function of the cycling frequency, which is established by the speed of the alternator, and thus it is a single speed, power transmission system like a directly shafted, engine driven compressor. A two- or three-speed AC motor can be made, at the expense of additional weight, by providing additional poles and windings with appropriate switching to energize or de-energize them.

2.1.2   Control of Air Flow

The following paragraphs briefly state the most obvious means of flow control in cabin pressurization systems:

1. Direct Engine Compressor Bleed to Cabin: A flow sensitive venturi used with a simple throttle valve meters the flow in accordance with the desired schedule. In some cases a simple venturi without a throttle may provide adequate flow regulation.

2. Shafted Compressors - Fixed Ratio on Constant Speed Engine: A flow sensitive venturi or probe is used to regulate an inlet throttle on the compressor; or, for an extended operating range of pressure and flow in an aerodynamic compressor, a preswirl inlet throttle is available. Fixed displacement compressors may require a spill valve to dump excess flow overboard.

3. Shafted Compressors - Variable Speed Transmission: A flow sensor regulates the speed ratio of the transmission.

4. Shafted Compressors - Multispeed Transmission: Speed ratio shift points are triggered by input speed sensitive switches. Flow is regulated as for a fixed speed compressor.

5. Bleed Driven Turbocompressors: The flow sensor regulates a throttle valve in the bleed air duct to the turbine or it regulates the area of the turbine nozzles. Thus, speed changes are made as required, to maintain the cabin flow schedule under varying conditions of compressor delivery pressure and available engine bleed pressure.

6. Hydraulic Drive: The flow sensor regulates the displacement of the engine driven pump, thus varying fluid flow and the speed of the fixed displacement hydraulic motor driving the compressor.

2.1.3   Other Controls

Depending upon the pressurization source, other controls not covered in Pars. 2.1.1 and 2.1.2 are required for proper and safe operation of the air supply system. Some of the more important functions are as follows:

1. A direct bleed system requires a fast acting shutoff valve for quickly stopping the flow to the cabin in an emergency. If an air cycle refrigeration system is used, it may be necessary to devise a minimum flow limiter to prevent full closure of the cooling turbine bypass valve when the bleed pressure is too low to force sufficient flow through the cooling turbine nozzles. A maximum flow limiter such as a sonic venturi may also be required as a safety device.

2. A quick acting mechanical drive shaft disconnect is good insurance against extensive damage to the powerplant, which might otherwise occur as a result of mechanical failure in an engine mounted compressor.

3. Fixed speed aerodynamic compressors may require a spill valve to prevent surging. A control that senses the compressor discharge Mach number can be used to regulate the spill valve.

4. In any separate variable speed compressor system, it may be desirable to provide cabin heating by increasing the compressor speed and throttling the air or by recirculating compressor discharge air into the inlet. In either case a downstream flow control causes the desired speed increase when the heat valve is moved toward the closed position.

2.2   Control of Cabin Pressure

The pressurized volume of the fuselage is usually pressure controlled by regulation of the outflow air. The magnitude of the uncontrolled cabin leakage is kept low enough to provide a finite air flow at all times through the outflow valve for pressure regulation purposes.

2.2.1   Isobaric Control

This term describes the mode of control that maintains a constant cabin altitude. It is generally used in all aircraft, and in most transports it is adjustable through a range from 1000 ft below sea level to 10,000 ft above sea level.

2.2.2   Differential Control

This term describes the mode of control that maintains a constant pressure difference between cabin and ambient, usually the normal operating pressure. This overrides the selected isobaric control when the latter would result in exceeding the differential pressure for which the structure is designed.

2.2.3   Rate Control

In transport aircraft a selectable rate of climb and descent is provided, with a range of selection usually between 200 and 2000 fpm. Combat type aircraft usually provide fixed rate limits as required by the applicable specification. The rate control limits the rate of change of cabin pressure toward the isobaric setting, but does not override the differential control.

2.2.4   Safety Valves

Safeguards are provided by:

1. Positive Pressure Relief - in addition to the outflow valve or valves, an independent control valve is provided to limit the maximum pressure in the cabin to one the structure can safely withstand in the event of a normal control malfunction. The setting of the relief valve is higher than the normal differential control limit by the small amount necessary to prevent overlapping functions between the two controls.

2. Negative Pressure Relief - a negative differential pressure valve is required to limit the collapsing pressure on the fuselage as might occur, for example, in a rapid descent from altitude. This valve can be combined with the positive pressure relief, or it can be an independent unit. A simple swing check valve will serve the purpose.

3. Emergency Pressure Release - Ref. 1 specifies that components must be installed to permit release of cabin pressure within the following time periods: 60 sec max-

imum for all aircraft employing ejection seats, escape capsules, or their equivalent, for all aircraft occupants; or 15 sec maximum for all other aircraft. These rapid pressure release provisions are associated with aircraft flying into advance combat zones where lower cabin pressure differentials are used.

2.2.5   Types of Controllers
Both pneumatic and electric regulators are in use for cabin pressure control, and the functional details are available from the manufacturers of this equipment.

2.2.6   Unpressurized Cabin Differential
The effective area, CA, of the outflow valve is usually established by the permissible cabin differential when in the unpressurized condition, that is, with the valve wide open. The flow restriction imposed by the valve and related ducting produces a small unavoidable pressure differential between the cabin and ambient when all other openings such as doors and windows are closed. To avoid discomfort to human occupants, due to an abrupt pressure increase (pressure "bump") when the last door is closed, or when the compressor flow is initiated, the flow restriction of the fully open valve and ducting must be kept small. Pressure losses of the order of 0.2 in. Hg are tolerable in transport systems, and higher values may be acceptable in combat aircraft.

In addition to the pressure loss of the valve installation, an additional pressure differential may be imposed by control requirements. To avoid this, the pressure controller must be designed with sufficient sensitivity to fully open the valve at or below the desired minimum pressure. This requires sufficient control sensitivity to produce a signal for a fully open valve at low differentials, and in the case of an all-pneumatic system, a vacuum booster may be required to furnish sufficient pneumatic power to a reasonably sized valve actuator.

A third significant factor contributing to the magnitude of the minimum differential is the location of the aircraft air exhaust. If the exhaust is located in an area where external aerodynamic pressures are different from ambient static, the cabin pressure will be affected by changes in aircraft speed, especially during take-off and landing. For example, an exhaust location in a high pressure region will produce an unavoidable cabin pressure increase during the takeoff run.

2.2.7   Control in Supersonic Aircraft:
As a supersonic aircraft accelerates or decelerates through the sonic speed region (Mach 1.0), an abrupt change in external static pressure occurs on the aircraft. This change is communicated to the cabin through the outflow valve discharge opening and to the controller through the static reference for the differential control mode. The result may be a very uncomfortable "bump" in cabin pressure, especially in the small pressurized volume of a fighter aircraft.

The transmission of the external pressure pulse through the outflow valve can be minimized and perhaps eliminated if the cabin/ambient pressure ratio is above the critical value of 1.89 (which may not be possible at low altitudes), and if the outflow valve actuator is not caused to move by the external disturbance. Furthermore, the disturbance will not affect the controller if it is operating in the isobaric mode sufficiently below the maximum differential. Therefore, in transport aircraft with high differential pressure settings and an appropriate outflow valve, operating procedures may be sufficient to eliminate the cabin pressure disturbance. However, in fighter

aircraft, the differential setting is usually low, and acceleration through Mach 1.0 must be done with the controller operating in the differential mode.

3.   CABIN LEAKAGE

Uncontrolled cabin leakage should be kept very low so that use can be made of exhaust cabin air for equipment cooling and general odor removal. Also, in the event of loss of the pressure source at high altitude, more time will be available for descent to a safe altitude. Leakage control is both a detail structural design problem and a fabrication quality control problem. Both are important.

The greatest leakage that can be tolerated is one that, together with essential overboard venting, totals less than the supply flow after inadvertent loss of a reasonable portion of the cabin pressurization source at maximum cabin differential. In a two compressor supply system, for example, the loss of one compressor might be called a reasonable failure condition. Under this condition the leakage must be low enough to permit adequate pressurization on the remaining single compressor for the duration of the flight.

To establish the allowable leakage rate for design purposes, the following example is presented for a two compressor airplane flying at 30,000 ft with an 8000 ft cabin altitude (22.22 in. Hg cabin pressure). The detail specification for this example requires maintaining an 8000 ft cabin on one compressor, as described in Table 3E-1.

Table 3E-1 - Specification for Two Compressor Airplane

Available flow from one compressor		45 lb/min
Toilet exhaust	5.0 lb/min	
Electronic compartment exhaust	20.0	
Evaporator water drains (vapor cycle)	2.0	
Miscellaneous control vents	1.0	
Margin for leakage growth	3.0	
Total controlled venting plus margin	31.0	31 lb/min
Permissible uncontrolled leakage at flight condition		14 lb/min

An equivalent leak orifice area can be calculated from the following compressible flow equation:

$$CA = \frac{w\sqrt{T_{cb}}}{60.4\, P_{cb}\, Z} = \frac{14\sqrt{460+70}}{(60.4)\,(22.22)\,(0.256)} = 0.945 \text{ in.}^2 \tag{3E-1}$$

In Eq. 3E-1, CA is the equivalent area in square inches of a hole that would pass the total leakage flow at the specified cabin pressure and temperature and flight altitude.

Z is the function of pressure ratio between cabin and ambient, defined by

$$Z = \sqrt{\left[\frac{P_a}{P_{cb}}\right]^{2/\gamma} - \left[\frac{P_a}{P_{cb}}\right]^{(\gamma+1)/\gamma}} \qquad (3E\text{-}2)$$

for pressure ratios between 1.0 and 0.53. For pressure ratios equal to and below 0.53, sonic velocity occurs in the orifice, $Z = 0.256$ and remains constant thereafter, and the equation no longer holds for the determination of orifice area. Note that the ambient may be either a true local ambient pressure (depending upon the hole location) defined as P_a, or actual pressure altitude, commonly noted as P_o or P_∞ in the literature.

For convenience, inspection tests for leakage rate are usually conducted on the ground, requiring that an equivalent leakage be computed for the test elevation and test cabin pressure. The ground test is conducted at the same pressure differential as in the design flight condition, to eliminate any change in leakage area CA due to change in differential pressure.

Flight loads and vibration may have a small effect on the leakage area, but it is believed to be negligible. The leakage permissible during ground test is obtained as follows, using the differential pressure for 8000 ft cabin altitude at 30,000 ft, and testing at a ground elevation of 500 ft:

$$P_a = 29.4 \text{ in.Hg abs. at 500 ft}$$

$$P_{cb} = 29.4 + (22.22 - 8.88) = 42.74 \text{ in. Hg abs.}$$

$$\frac{P_a}{P_{cb}} = \frac{29.4}{42.74} = 0.69$$

From this pressure ratio, the function $Z = 0.241$ (from Eq. 3E-2) and

$$w = \frac{60.4 CA P_{cb} Z}{\sqrt{T_{cb}}} \qquad (3E\text{-}3)$$

$$= \frac{(60.4)(0.945)(42.74)(0.241)}{\sqrt{460 + 70}}$$

$$= 25.6 \quad \text{lb/min}$$

Actual measurement of the leakage can be accomplished (1) by direct inflow readings, (2) by timed pressure decay, or (3) by instantaneous cabin rate of climb. Direct inflow readings are appropriate for small volumes with fairly large leakage rates where the decay time is too short to obtain reliable data.

Timed pressure decay over a small increment of pressure change or instantaneous rate readings are appropriate for large volumes with relatively low leakage rates. Direct flow readings require

steady-state conditions and are difficult to obtain in large volumes with low leakage without a sensitive rate of pressure change indicator to aid in establishing the steady state.

For conversion of leakage flow into timed rate of pressure decay or instantaneous rate of climb, the following equations are derived by differentiating the equation of state with respect to time:

$$pV = WRT \text{ for } p \text{ in lb/ft}^2, W \text{ in lb}$$

$$\text{or} \quad PV = WRT/70.7 \text{ for P in in.Hg}$$

$$\text{Then} \quad \frac{dW}{d\tau} = w = 70.7 \frac{V}{RT} \frac{dP}{d\tau}$$

$$\text{or} \quad w = \frac{70.7}{53.3} \frac{V}{T} \frac{dP}{d\tau} \tag{3E-4}$$

Since the reading of the rate of climb indicator (dH/dτ, ft/min) is

$$\frac{dH}{d\tau} = \frac{70.7}{\rho g} \frac{dP}{d\tau} \left(\text{as obtained from the buoyancy equation } dP = \frac{\rho g dH}{70.7} \right)$$

the leakage in terms of rate of climb is

$$w = \frac{V(\rho g)}{53.3T} \frac{dH}{d\tau} \tag{3E-5}$$

These equations are also useful in establishing inspection test leakage limits for duct systems.

4. EMERGENCY RELEASE OF CABIN PRESSURE

The time required to release the cabin pressure is of interest to the designer in establishing effective emergency procedures for fighting fire and smoke in the cabin in flight and in providing rapid abandonment procedures in combat aircraft. The equations for making estimates of pressure release time were obtained from the literature (Ref. 5) and are presented below.

In practice the aircraft will almost always be descending while the pressure is being released, and the actuation time of the supply air shutoff and cabin pressure release valves may be appreciable. For accurate estimates of time of pressure decay, it will be necessary to know the descent path of the aircraft and the rate of change of inflow and outflow as the valves are actuated, and then to perform a stepwise calculation of pressure versus time. Temperature is usually assumed constant, owing to the heat transfer from cabin surfaces and the relatively long pressure decay time.

For the period during which the pressure ratio between cabin and ambient is supercritical, the following time is required to decay from $P = P_1$ to $P = P_2$:

$$\tau' = \frac{V(\rho_1 g)}{w_1} \ln\left[\frac{w_1 - w_s}{w_2 - w_s}\right] \tag{3E-6}$$

where at any instant

$$w = \frac{15.63\ CAP_{cb}}{\sqrt{T_{cb}}} \quad \text{from Ref. 7} \tag{3E-7}$$

Following this, the time of pressure decay in the subcritical pressure ratio period is given by

$$\tau'' = \frac{266V}{RCA\sqrt{P_a T_{cb}}}\left[\sqrt{\Delta P_1} - \sqrt{\Delta P_2}\right] + \frac{8.35 V w_s}{RP_a(CA)^2}\ln\left[\frac{w_1 - w_s}{w_2 - w_s}\right] \tag{3E-8}$$

where at any instant the subcritical flow can be found from Fliegner's approximation:

$$w = 31.8 CA\sqrt{\frac{P_a(P_{cb} - P_a)}{T_{cb}}} \quad \text{from Ref. 5} \tag{3E-9}$$

and where the subscripts 1 and 2 denote initial and final conditions, respectively.

4.1 Low Pressure Ducting to Outflow Valve

When low pressure cabin ducts are used to conduct exhaust air from the cabin to the outflow valve, the ducts may require a relief damper to prevent collapse if the outflow valve is rapidly opened for pressure release. (See Fig. 3E-1.) Alternatively, the duct can be designed to withstand the collapsing pressure imposed during transient high-flow periods.
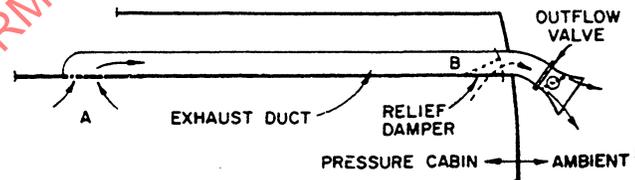

Figure 3E-1 - Low pressure exhaust duct

The pressure drop from the cabin, A, to the end of the low pressure duct, B, is the collapsing pressure at B, and can be calculated from known duct geometry and the maximum anticipated instantaneous flow.

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[1]Ambient may or may not be freestream or pressure altitude

5.   ENERGY RECOVERY FROM CABIN AIR DISCHARGE

It is possible to recover some of the energy expended in compression of fresh air for the cabin by releasing the cabin exhaust air through an aft facing nozzle, thereby producing propulsive thrust. The nozzle must be a variable area type in order to provide cabin pressure regulation and obtain high jet velocity. An example of the value of this scheme is given for an aircraft flying at Mach 0.8 at 40,000 ft (P_a = 5.54 in.Hg) and releasing 50 lb/min of 67 $^\circ$F air from an 8000 ft cabin (P_{cb} = 22.22 in.Hg).

The nozzle pressure ratio is

$$\frac{P_{cb}}{P_a} = \frac{22.22}{5.54} = 4.01$$

Assume a 5% loss in duct and nozzle friction; then

$$\frac{P_{cb}}{P_a} = (0.95)(4.01) = 3.81$$

In general: $\dfrac{P_{cb}}{P_a} = (1 + 0.2M^2)^{3.5}$ (See Eq. 1B-62 of AIR1168/1)

Solving: $M = 1.53$ (velocity of the air jet)

In general: $\dfrac{T}{T_j} = 1 + 0.2M^2$ (See Eq. 1B-56 of AIR1168/1)

Solving: $\dfrac{T_j}{T} = \dfrac{T_j}{T_{cb}} = 0.6811$

In general: $a = \sqrt{\gamma g R T} = \sqrt{(1.4)(32.2)(53.3)T} = 49\sqrt{T}$, or $a_j = 49\sqrt{T_j}$

(See Eq. 1B-50 of AIR1168/1)

and $a_{cb} = 49\sqrt{T_{cb}} = 49\sqrt{67 + 460} = 49\sqrt{527} = 1125$ fps

Then $\dfrac{a_j}{a_{cb}} = \sqrt{T_j/T_{cb}} = \sqrt{0.6811} = 0.8253$

From the definition for Mach Number:

$$M = \frac{V_{ex}}{a}$$

Then $V_{ex} = Ma_j = Ma_{cb}\dfrac{a_j}{a_{cb}}$