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AEROSPACE INFORMATION REPORT

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Compartment Decompression Analysis

RATIONALE

This report provides data and analysis methods for calculation of internal and external airplane compartment pressures during rapid discharge of cabin pressure. No industry standard exists for analysis of rapid compartment decompression. Analysis reduces the need for flight testing. Numerous sources each address particular aspects of compartment decompression analysis. This document compiles them into a concise, comprehensive report.

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1. SCOPE

This report provides data and general analysis methods for calculation of internal and external, pressurized and unpressurized airplane compartment pressures during rapid discharge of cabin pressure. References to the applicable current FAA and EASA rules and advisory material are provided. While rules and interpretations can be expected to evolve, numerous airplanes have been approved under current and past rules that will have a continuing need for analysis of production and field modifications, alterations and repairs. The data and basic principles provided by this report are adaptable to any compartment decompression analysis requirement.

1.1 Purpose

The purpose of this report is to provide a method to predict transient differential pressures across internal pressure barriers (such as floor panels and bulkheads), within external compartments adjacent to the pressure vessel (such as fairings and tailcone) and the occupied compartment pressure altitudes resulting from cabin decompression events prescribed by FAA and JAA/EASA regulations and Special Conditions. The analysis methods in this report can be used as a design tool to determine the following:

- The maximum permissible openings in the pressure vessel from loss of antennae, duct couplings, seals, etc… that will limit maximum transient cabin pressure altitude to acceptable levels. If the pressure vessel opening can result from a fatigue crack, the allowable opening size may define the required structural inspection intervals.
- The minimum permissible vent openings through internal partitions and structure that will limit panel pressure differentials to structurally acceptable levels during decompression events.
- The minimum permissible vent openings through external fairings and structure that will limit panel pressure differentials to structurally acceptable levels during decompression events.
- The maximum permissible cockpit door weight and door unlatching pressure to limit cockpit partition loads to acceptable levels during a cockpit structure decompression.
- The airplane descent rate required to limit maximum transient cabin pressure altitude to acceptable levels during emergency descent, which may size lift dump and drag devices and their required extension/operating speed capabilities.

The analysis methods in this report can also be used as a validation tool for a specified aircraft configuration. Predicted pressure differentials that would result from a decompression event for a specified airplane configuration can be used for structural analysis and substantiation. Analysis to determine cabin pressure altitudes can be used in lieu of flight testing.

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 noted date. 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 International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA),www.sae.org.

AIR825/1 Introduction to Oxygen Equipment for Aircraft

AIR825/8 Continuous Flow Oxygen Systems

AIR825/9 Demand Oxygen Systems

AIR1168/1 Thermodynamics of Incompressible and Compressible Fluid Flow; SAE Aerospace Applied Thermodynamics Manual

AIR1168/5 Aerothermodynamic Test Instrumentation and Measurement; SAE Aerospace Applied Thermodynamics Manual

AIR1168/6 Characteristics of Equipment Components, Equipment Cooling Systems Design, and Temperature Control System Design, SAE Aerospace Applied Thermodynamics Manual

AIR1168/7 Aerospace Pressurization System Design, SAE Applied Thermodynamics Manual

2.1.2 EASA Publications

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452, Koeln, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

AMC 20-128A Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure

CS-23 Certification Specifications for Normal, Utility, Aerobatic and Commuter Category Aeroplanes

CS-25 Certification Specifications for Large Aeroplanes

EU OPS 1 Common technical requirements and administrative procedures applicable to commercial transportation by aircraft

2.1.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Ave., SW, Washington, DC 20591, Tel: 866-835- 5322, www.faa.gov.

AC 20-128A Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure, Initiated by ANM-110, 3/25/97

AC 25-20 Pressurization, Ventilation and Oxygen Systems Assessment for Subsonic Flight including High Altitude Operation, FAA Advisory Circular, Initiated by ANM-110, 9/10/1996

AC 25-22 Certification of Transport Airplane Mechanical Systems, FAA Advisory Circular, Initiated by ANM-110, 3/14/2000

14 CFR Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes

FAA Memorandum from Manager, Transport Airplane Directorate, ANM-100- Certification of Strengthened Flightdeck Doors on Transport Category Airplanes, Dated November 6, 2001, Revised December 3, 2002

FAA Memo ANM-03-112-16, March 24, 2006- Interim Policy on Amendment 25-87 Requirements

2.1.4 NACA Publications

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161 and from the NACA Technical Reports Server at http://naca.larc.nasa.gov.

WR-L-23 Variation With Mach Number of Static and Total Pressures Through Various Screens; Originally Issued as Confidential Bulletin No. L5F28, Alfred A. Adler, Feb. 1946

Report 933 Performance of Conical Jet Nozzles in Terms of Flow and Velocity Coefficients; Ralph E. Grey, Jr. and H. Dean Wilstead, Sept. 7, 1948

Report 1235 Standard Atmosphere- Tables and Data for Altitudes to 65,800 Feet, NACA Langley Aeronautical Laboratory (Langley Field, Va, United States); International Civil Aviation Organization (Montreal, Canada.), 1955

TN 1947 Investigation of Flow Coefficients of Circular, Square, and Elliptical Orifices at High Pressure Ratios; Edmund E. Callaghan and Dean T. Bowden, Sept 1949

TN 3359 An Investigation of Drains Discharging Liquid into Subsonic and Transonic Streams; Allen R. Vick and Frank V. Silhan, March 1955

TN 3466 An Investigation of the Discharge and Drag Characteristics of Auxiliary-Air Outlets Discharging into a Transonic Stream; Paul E. Dewey and Allen R. Vick, July 1955

TN 3924 Discharge Coefficients for Combustor-Liner Air-Entry Holes II- Flush Rectangular Holes, Step Louvers, and Scoops; Ralph T. Dittrich, April 1958

2.1.5 NASA Publications:

Available from NASA, Documentation, Marshall Space Flight Center, AL 35812 and from the NASA Technical Reports Server at http://ntrs.nasa.gov.

CR-61241 Experimental Determination of General Venting Characteristics, NASA Contractor's Report, Baker, J. M.; Glasgow, R. M.; Walters, W. P., George C. Marshall Space Flight Center, Huntsville, Alabama, July 1968

NASA-STD-3000 Man-Systems Integration Standards, Revision B, July 1995

TM X-53734 Compartment Venting and Pipe Flow With Heat Addition, NASA Technical Memorandum, Struck, H. G. and Harkins, John A., George C. Marshall Space Flight Center, Huntsville, Alabama, April 23, 1968

2.1.6 U.S. Federal Register

Available from Government Printing Office, 732 North Capitol St. NW, Washington, DC 20401 and from http://www.gpoaccess.gov/fr.

US Federal Register Vol. 45, page 60172, Sept. 11, 1980, Amendment 25-54: Airworthiness Review Program-Amendment No. 8A: Aircraft, Engine, and Propeller Airworthiness, and Procedural Amendments

US Federal Register Vol. 51, No. 52, Pages 9432-9433, Tuesday, March 18, 1986, Docket No. 23243, Withdrawal of Notice of Proposed Rulemaking, "Pilot Oxygen Mask Requirements"

US Federal Register Vol. 55, page 13477, April 10, 1990, Amendment 25-71: Improved Structural Requirements for Pressurized Cabins and Compartments in Transport Category Airplanes

US Federal Register Vol. 60, No. 177, Page 47464, September 13, 1995, Docket No. NM-111, Special Condition No. 25-ANM-106, Final Special Conditions: Israel Aircraft Industries Model Galaxy Series Airplane, High Altitude Operation

US Federal Register Vol. 65, No. 30, Pages 7283-7287, Monday, February 14, 2000, Docket No. CE154, Special Condition No. 23-102-SC, Final Special Conditions: Cessna Aircraft Company, Model 525A, High Altitude Operation

2.1.7 U.S. Government Publications

Available from U.S. Government Printing Office, Washington, D.C. and from the NASA Technical Reports Server at http://ntrs.nasa.gov/

U.S. Standard Atmosphere, 1976, U.S. Government Printing Office, Washington, D.C.

2.1.8 National Transportation Safety Board Publications

Available from The National Transportation Safety Board Headquarters, 490 L'Enfant Plaza, SW, Washington, DC 20594 and from http://www.ntsb.gov/ntsb/query.asp.

NTSB/AAR-89/0- Aircraft Accident Report, ALOHA AIRLINES, FLIGHT 243, NEAR MAUI, HAWAII, APRIL 28, 1988, BOEING 737-200, N73711

2.2 Other Applicable References

82009- Compressible Flow of Gases, ESDU International, 27 Corsham St., London N1 6UA, UK, Feb. 2004

Anderson, John D., Jr.- Introduction to Flight, McGraw-Hill Book Co., New York, 1978

Dutton, J. Craig and Coverdill, Robert E.- Experiments to Study the Gaseous Discharge and Filling of Vessels, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign Urbana, IL 61801, USA, Published in International Journal of Engineering Education, Vol 13, No 2, pg 123-134, 1997

Haber, Fritz- On the Physical Process of Explosive Decompression, USAF School of Aviation Medicine, Randolph Field, Texas, October 1950, Published in the Journal of Aviation Medicine, December 1950

Haber, Fritz and Clamann, George- Physics and Engineering of Rapid Decompression, A General Theory of Rapid Decompression, , USAF School of Aviation Medicine, Randolph Field, Texas, August 1953

Karlsson, Björn and Quintiere, Jim- Enclosure Fire Dynamics, CRC Press LLC, Boca Raton, Fl, 2000

Kent's Mechanical Engineers' Handbook, Power Volume, J. Kenneth Salisbury, Editor, John Wiley & Sons, Inc., New York, NY, 12th Edition, 1954

Miller, Richard W.- Flow Measurement Engineering Handbook, McGraw-Hill Book Co., New York, NY, 3rd Edition, 1996

Veldman, Roger L.- Enhancing Commercial Aircraft Survivability Via Active Venting, Doctorate Dissertation Submitted to Western Michigan University, Department of Mechanical and Aeronautical Engineering, Bell and Howell Information and Learning Co., Ann Arbor, MI, 2001

2.3 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

AIAA-1994-1411- DECOMP, A Multi-Compartment Rapid Decompression Analysis Code, Wayne E. Frazer, E-Systems, IN:AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 35th, Hilton Head, SC, Apr. 18-20, 1994, Technical Papers. Pt. 2 (A94-23876 06-39), Washington, DC, American Institute of Aeronautics and Astronautics, 1994, p. 829-832

AIAA-2004-0054- Bréard, Cyrille and Lednicer, David- A CFD Analysis of Sudden Cockpit Decompression, Analytical Methods, Inc., AIAA Aerospace Sciences Meeting and Exhibit, 2004

AM 67-14- An Evaluation of the Potential Decompression Hazards In Small Pressurized Aircraft, John J. Swearingen, FAA Office Of Aviation Medicine, June 1967

AM 70-12- Physiological Tolerable Decompression Profiles for Supersonic Transport Type Certification, Stanley R. Mohler, FAA Office Of Aviation Medicine, July 1970

AM-99/4- Concepts Providing for Physiological Protection After Aircraft Decompression in the Altitude Range of 60,000 to 80,000 Feet above Sea Level, Robert P. Garner, FAA Office Of Aviation Medicine, February 1999

ARP1270A- Aircraft Pressurization Criteria, SAE, 400 Commonwealth Drive, Warrendale, PA, 2000-04

SP-8060- Compartment Venting, NASA Special Publication, NASA Space Vehicle Design Criteria (Structures), November 1970

TR 54-446- A Method for More Accurate Design Estimation of Air Leakage from Cabins and Cockpits of Pressurized Aircraft, A. B. Nutt, WADC Technical Report, Sept. 1954

Demetriades, Serge T.- Decompression of a Punctured Pressurized Cabin, Northrop Corp./Noriar Division, Sept. 1, 1959, ASTIA AD 229671

Mohler, Stanley R., M.D.- Quick Response by Pilots Remains Key to Surviving Cabin Decompression, Human Factors and Aviation Medicine, Vol. 47, No. 1, Flight Safety Foundation, 601 Madison Street, Suite 300, Alexandria, Virginia U.S. 22314-1756

Muraca, R. J.- A Method for Determining the Time-Dependant Pressures in a Series of Chambers Connected to an External Pressure Whose Variation with Time is Known, Master's Thesis, University of Virginia, 1968 (Available from the author on request, care of NASA Langley Research Center)

Smith, Chester W.- Calculation of Flow of Air and Diatomic Gases, Published in the Journal of Aeronautic Sciences, June 1946

2.4 Definitions

Decompression and depressurization are often used interchangeably. The definitions used in this report follow.

CREW RECOGNITION TIME- The total time from when the flight crew receives indication of excessive cabin altitude to the beginning of the emergency descent. Actions required during this period will typically include donning of oxygen masks, deploying passenger oxygen masks, configuring lift and drag devices for descent and, if necessary, slowing airplane to the descent airspeed. A time of 17 seconds is noted as acceptable in FAA AC 25-20, but a shorter time may also be accepted if justified.

DECOMPRESSION- An inadvertent or unintended reduction in cabin pressure, which can result from equipment failures or malfunctions or from pressure vessel failures.

DEPRESSURIZATION- A reduction in cabin pressure, typically performed automatically by the cabin pressurization control system such as to dump cabin pressure on landing, or manually in the case of windshield cracks, cockpit smoke evacuation, excessive cabin pressure differential, door unlatch indications, etc.

DISCHARGE COEFFICIENT- A correction factor used for figuring volume flow rate of a fluid through an orifice that includes the effects of contraction and turbulence loss. It is the ratio of the real mass flow rate to the mass flow rate if the flow were isentropic.

FLOW COEFFICIENT- A correction factor used for figuring volume flow rate of a fluid through an orifice that includes the effects of contraction and turbulence loss (covered by the coefficient of discharge), plus the compressibility effect, and the effect of an upstream velocity other than zero.

MMO- Maximum allowable operating Mach number

RAPID DECOMPRESSION- An unintended reduction in cabin pressure at a rate of 2100 m (7000 feet) per minute or more, generally accompanied by “misting” - or the formation of a cloud in the cabin as the temperature and the dew point in the cabin converge and water vapor condenses into visible droplets. [1] Some decompression scenarios, such as complete loss of inflow are still classified as rapid decompressions though the rate is significantly less than 2100 m/min. The potential hazards of a Rapid Decompression are that the crew could be incapacitated by hypoxia, resulting in loss of the airplane or that the passengers could suffer permanent neurological damage from oxygen deprivation.

SLOW DECOMPRESSION- An unintended reduction in cabin pressure that occurs if the cabin altitude rises at a rate of a few hundred feet per minute or less.[2] A Slow Decompression is so gradual that it is not detectable to occupants. The potential hazard of a Slow Decompression is that it may not be detected until the flight crew becomes incapacitated, potentially resulting in loss of the airplane.

VERY RAPID DECOMPRESSION- A violent expansion and noise from cabin air released under pressure.[3] Erroneously called an “Explosive Decompression” because of the loud bang that may occur from the sudden expansion of cabin air. This type of decompression occurs so suddenly that no crew action is possible. The potential hazards of a Very Rapid Decompression are that internal floor panels or partitions may be collapsed onto critical systems or become projectiles or that the sudden discharge of air into normally unpressurized external compartments may result in a hazardous loss of structural integrity that could cause loss of the airplane.

VMO- Maximum allowable operating airspeed

2.5 Symbols

TABLE 1- VARIABLE DEFINITIONS

Symbol	Definition	SI Units	USCS Units
A	Area	m^2	ft^2
A_{edge}	Area Between Edge of Door and Frame	m^2	ft^2
A_{top}	Area Between Top of Door and Frame	m^2	ft^2
C	Flow Coefficient	N/A	N/A
C_{BF}	Butterfly Valve Flow Coefficient	N/A	N/A
C_B	Flow Coefficient from Butterfly Thickness	N/A	N/A
C_D	Discharge Coefficient	N/A	N/A
C_θ	Flow Coefficient from Butterfly Angle	N/A	N/A
CA	Effective Flow Area	m^2	ft^2
CA_o	Valve Full Open Effective Flow Area	m^2	ft^2
CA_p	Valve Partially Open Effective Flow Area	m^2	ft^2
D	Diameter	m	ft
D_u	Upstream Diameter	m	ft
D_d	Orifice or Nozzle Throat Diameter	m	ft
dt	Time Increment	seconds	seconds
H_d	Door Height	m	ft
H	Pressure Altitude	m	ft

[1] Mohler.

[2] Mohler.

[3] NTSB Report NTSB/AAR-89/03, pg 5.

J_d	Door Polar Moment of Inertia	$kg \cdot m^2$	$lb \cdot ft^2$
m_d	Door Mass	kg	lb
M	Mach Number	N/A	N/A
k	Polytropic Constant	N/A	N/A
P	Pressure	Pa	lbf/ft^2
P_1	Initial Pressure	Pa	lbf/ft^2
P_2	Final Pressure	Pa	lbf/ft^2
P_u	Upstream Pressure	Pa	lbf/ft^2
P_{u1}	Initial Upstream Pressure	Pa	lbf/ft^2
P_{u2}	Final Upstream Pressure	Pa	lbf/ft^2
P_d	Downstream Pressure	Pa	lbf/ft^2
P_S	Static Air Pressure	Pa	lbf/ft^2
q	Dynamic Pressure	Pa	lbf/ft^2
r	Pressure Ratio = $\frac{P_d}{P_u}$	N/A	N/A
r_b	Ratio of Butterfly Thickness to Diameter	N/A	N/A
r_c	Critical Pressure Ratio = $\left(\frac{P_d}{P_u}\right)_c$	N/A	N/A
Re_D	Reynolds Number Based on Duct Diameter	N/A	N/A
t	Time	seconds	seconds
t'	Time for Pressure Decay for Supercritical Flow	seconds	seconds
t"	Time for Pressure Decay for Subcritical Flow	seconds	seconds
t_c	Valve Time to Travel Full Open to Full Closed	seconds	seconds
t_o	Valve Time to Travel Full Closed to Full Open	seconds	seconds
T	Temperature	K	°R
T_u	Upstream Static Temperature	K	°R
Th	Butterfly Thickness	m	ft
V	Volume	m^3	ft^3
V_1	Initial Volume	m^3	ft^3
V_2	Final Volume	m^3	ft^3
V_C	Calibrated Airspeed		KCAS
w	Weight	kg	lb
w_1	Initial Weight	kg	lb
w_2	Final Weight	kg	lb
w_d	Door Width	m	ft
$\dot{w}$	Gravimetric Mass Flow Rate	kg/s	lb/s
$\dot{w}_{in}$	Gravimetric Mass Inflow Rate	kg/s	lb/s

$\dot{w}_{out}$	Gravimetric Mass Outflow Rate	kg/s	lb/s
$\dot{w}_{out1}$	Initial Gravimetric Mass Outflow Rate	kg/s	lb/s
$\dot{w}_{out2}$	Final Gravimetric Mass Outflow Rate	kg/s	lb/s
x_b	Butterfly Valve Thickness	m	ft
x_d	Door Thickness	m	ft
Y	Expansion Factor	N/A	N/A
α_d	Door Angular Acceleration	rad/s^2	rad/s^2
δ	Density (Gravimetric)	kg/m^3	lb/ft^3
δ_1	Initial Density (Gravimetric)	kg/m^3	lb/ft^3
δ_2	Final Density (Gravimetric)	kg/m^3	lb/ft^3
β	Geometric Diameter Ratio = $\frac{D_d}{D_u}$	N/A	N/A
ϕ	Theoretical Compressibility Factor	N/A	N/A
γ	Ratio of Specific Heats for Air	N/A [4]	N/A
ν_1	Initial Specific Volume	m^3/kg	ft^3/lb
ν_2	Final Specific Volume	m^3/kg	ft^3/lb
θ	Butterfly Angle from Closed	degrees	degrees
θ_d	Door Angle from Closed	radians	radians
θ_i	Initial Butterfly Angle from Closed	degrees	degrees
τ	Time Constant	seconds	seconds
ω_d	Door Angular Velocity	rad/s	rad/s

[4] Air Ratio of Specific Heats will vary with temperature. For room temperature air, a value of 1.40 may be used.

TABLE 2- VALUES OF CONSTANTS

Symbol	Definition	SI Units	USCS Units
a	Temperature Lapse Rate	0.006 5 K/m	0.00356616 °R/ft
B	Constant, $g_0 \times \mathrm{Log}(e) / (R_a' \times T^*)$	6.848 317×10^{-5} m^{-1}	2.087367×10^{-5} ft^{-1}
g_C	Gravitational Constant	1 kg·m/N·s^2	32.17405 ft/s^2
g_0	SL Gravitational Acceleration	9.806 65 m/s^2	32.17405 ft/s^2
H*	Altitude at the Tropopause	11 000 m	36 089.24 ft
n	Constant, $g_0 / (R_a' \times a)$	5.256 16	5.25616
P_0	SL Standard Air Pressure	101 325.0 Pa	2116.216 lbf/ft^2
R_a	Air Ideal Gas Constant	287.04 m^2/s^2·K	53.3505 ft·lbf/lbm·°R
R_a'	Air Ideal Gas Constant	287.04 m^2/s^2·K	1716.5 ft^2/s^2·°R [5]
T_0	SL Standard Air Temperature	288.16 K	518.688°R
T*	Air Temperature at the Tropopause	216.66 K	389.988°R
V_0	SL Standard Speed of Sound	340.43 m/s	1116.89 ft/s (661.74 Kt)

2.6 Terminology

AC Advisory Circular

AFM Airplane Flight Manual

APU Auxiliary Power Unit

ASME American Society of Mechanical Engineers

ASTIA Armed Services Technical Information Agency

CFD Computational Fluid Dynamics

CFR Code of Federal Regulations

CS Certification Specification

EASA European Aviation Safety Agency

ECS Environmental Control System

FAA Federal Aviation Authority

FPA Feet Pressure Altitude

ICAO International Civil Aviation Organization

JAA Joint Aviation Authority

[5] A value of 1716.5 ft^2/s^2-°R is used in this report for the Air Ideal Gas Constant only in equations from NACA Report 1235. It has been assigned the symbol R_a' to distinguish it from the value of 53.5305 ft·lbf/lbm·°R for all other occurrences in this report.

JAR	Joint Aviation Regulation
KCAS	Knots Calibrated Airspeed
Ln	Naperian Logarithm
Log	Base 10 Logarithm
MMEL	Master Minimum Equipment List
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
SI	Systeme International
SL	Sea Level
USCS	United States Customary System

3. REQUIREMENTS FOR COMPARTMENT DECOMPRESSION ANALYSES

Airplane cabin pressurization has made high altitude flight safe, comfortable and practical. Considerable effort goes into ensuring that cabin decompression does not cause injury to the crew or passengers. Flight and ground testing are used for design and development, but they are not the only tools for evaluation of the effects of cabin decompression. Analysis methods are available that can be used in lieu of expensive and potentially hazardous testing.

Cabin decompressions fall roughly into three categories:

Slow- Decompressions or depressurizations that are so gradual that they may not be detectable to occupants. The potential hazard of Slow Decompressions are that they may not be detected until the flight crew becomes incapacitated, potentially resulting in loss of the airplane. Monitoring and annunciation of loss of cabin pressure are required to prevent crew incapacitation or injury to passengers. Typical certification requirements are defined by 14 CFR/CS 25.841.

Rapid- Decompressions or depressurizations that occur so rapidly that immediate, rapid descent is necessary to prevent crew incapacitation or permanent injury to passengers. The potential hazards of Rapid Decompressions are that the crew could be incapacitated by hypoxia, resulting in loss of the airplane or that the passengers could suffer permanent neurological damage from oxygen deprivation. During the descent, the cabin altitude-time history should not exceed what is accepted as safe for the occupants. Typical certification requirements are defined by 14 CFR/CS 25.841.

Very Rapid- Decompressions that occur so suddenly that no crew action is possible. The potential hazards of Very Rapid Decompressions are that internal floor panels or partitions may be collapsed onto critical systems or become projectiles or that the sudden discharge of air into normally unpressurized external compartments may result in a hazardous loss of structural integrity that could cause loss of the airplane. The barriers to free flow of air should be vented to limit the build up of pressure or else be designed to have the strength to withstand the transient pressure differentials. Typical certification requirements are defined by 14 CFR/CS 25.365.

Analysis is not necessary for slow decompressions, because a decompression slow enough that it is not likely to be detected allows ample time for crew response following annunciation of excessive cabin altitude. Analyses of Rapid and Very Rapid Decompressions use generally similar methods with the following significant differences:

Rapid Decompressions

- Except for when compartments are isolated by deliberate pressure barriers, the entire pressure vessel can be treated as a single volume. Calculations tend to be simple and straightforward.
- The analysis is complicated by continuously changing conditions of pressurization inflow rate and external pressure during the descent. Complete, derived solutions are not available except for a few very simple scenarios.
- The output of the analysis is the predicted cabin pressure altitude- time history during the decompression and descent.

Very Rapid Decompressions

- The decompression occurs so suddenly that it is assumed that all internal and external partitions subjected to the discharge of cabin pressure impede the air flow and develop pressure differentials. The analysis tends to be relatively complex, because of the numerous volumes that exchange air.
- The outputs of the analysis are the peak pressure differentials across the pressure barriers.

This report is divided into three sections. The first section provides basic analysis methods applicable to all forms of cabin decompression analysis. The second section provides detailed analysis criteria and procedures for Very Rapid Decompression while the third section addresses Rapid Decompression.

3.1 Maximum Cabin Altitude During a Decompression

Airplanes approved for high altitude flight are required by FAA, JAA and EASA regulations and Special Conditions to prevent exposure of the occupants to pressure altitudes that could cause permanent physiological harm or crew incapacitation during decompression events. The portion of the FAA rule applicable to the purpose of this report is:

14 CFR § 25.841 Pressurized cabins.

(a)Pressurized cabins and compartments to be occupied must be equipped to provide a cabin pressure altitude of not more than 8,000 feet at the maximum operating altitude of the airplane under normal operating conditions.

(1)If certification for operation over 25,000 feet is requested, the airplane must be designed so that occupants will not be exposed to cabin pressure altitudes in excess of 15,000 feet after any probable failure condition in the pressurization system.

(2)The airplane must be designed so that occupants will not be exposed to a cabin pressure altitude that exceeds the following after decompression from any failure condition not shown to be extremely improbable:

(i)Twenty-five thousand (25,000) feet for more than 2 minutes; or

(ii)Forty thousand (40,000) feet for any duration.

(3)Fuselage structure, engine and system failures are to be considered in evaluating the cabin decompression.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-38, 41 FR 55466, Dec. 20, 1976, Amdt. 25-87, 61 FR 28695, June 5, 1996]

The altitude-time limits for several typical high altitude special conditions are shown in FIGURE 1.

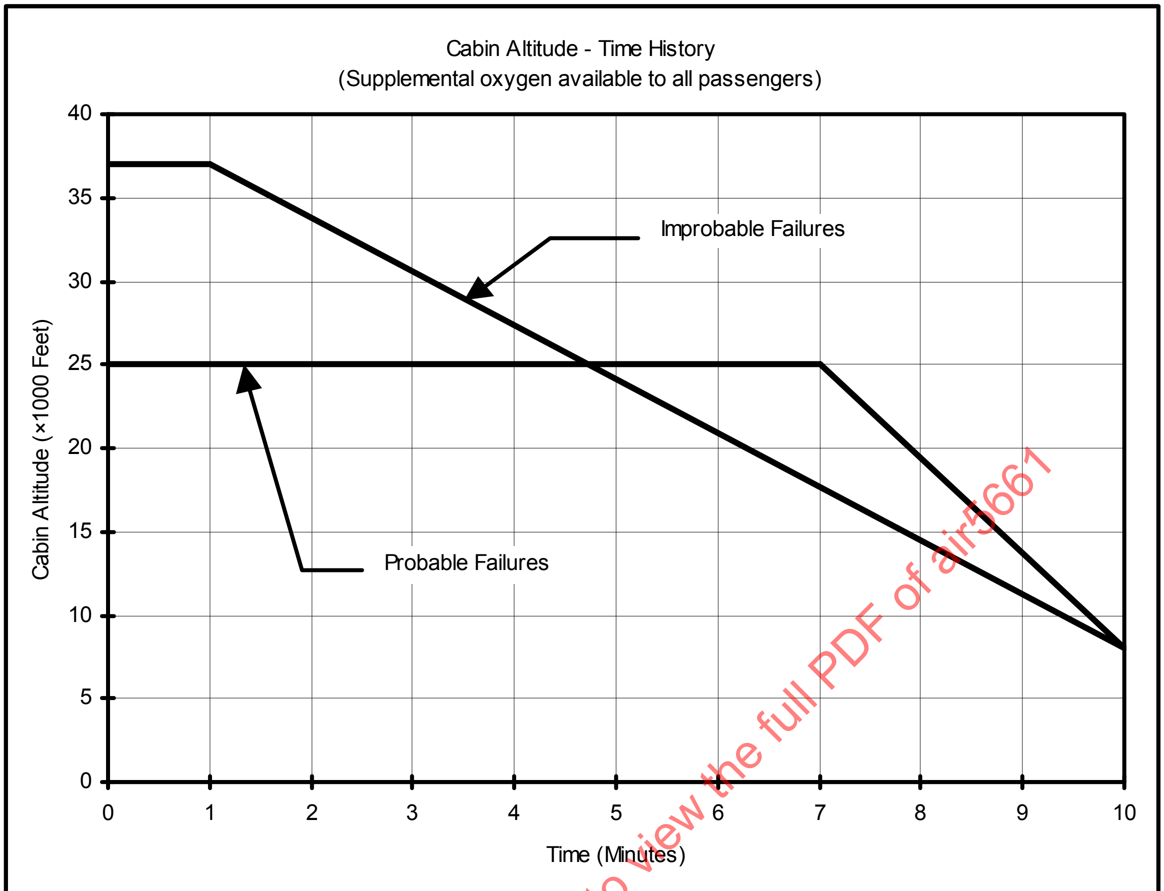

FIGURE 1- CABIN ALTITUDE-TIME LIMITS FOR TYPICAL HIGH ALTITUDE SPECIAL CONDITIONS [6]

Requirements comparable to 14 CFR §25.841(a) do not presently exist in 14 CFR Part 23 or CS 23/25. Requirements for high altitude airplanes approved under one of these other sets of rules are applied by Special Conditions. However, even if cabin altitudes during decompression are not explicitly limited by rules, system safety analysis for compliance with 14 CFR/CS 23/25.1309 will require that limits to cabin altitudes during decompressions be established to show hypoxic hazard to occupants from decompressions is prevented.

FAA Interim Policy Memo ANM-03-112-16, Dated March 24, 2006 provides a methodology acceptable to the FAA for request for exemption from the requirements of §25.841(a)(2)(i) and (ii), applicable only to decompressions following an engine rotor non-containment hitting the pressurized cabin for airplanes with wing-mounted engines. TABLE 3 provides the criteria from the memo.

TABLE 3- FAA INTERIM POLICY ALLOWABLE EXPOSURE TIME VS ALTITUDE

Cabin Pressure Altitude [meters]	**[feet]**	**Maximum Total Exposure Time [minutes]**
Above 13 716	(45 000)	0
Above 12 192	(40 000)	1
Above 7620	(25 000)	3
Above 3048	(10 000)	6

[6] These typical High Altitude Special Conditions also provide the following Alternate Criteria:
Probable Failures- Cabin Altitude shall not exceed 25 000 Ft for more than 2 min & 30 000 Ft maximum.
Improbable Failures- Cabin Altitude shall not exceed 25 000 Ft for more than 2 min & 40 000 Ft maximum.

3.2 Pressure Differentials Across Internal Barriers Due to Sudden Cabin Decompression

If an opening suddenly occurs in the pressure vessel, the escape of air can cause significant pressure loads on internal partitions and floor panels. Damage to internal pressure barriers, such as collapse of floor panels that cause damage to flight controls systems, can result in loss of the airplane.

14 CFR/CS 25.365 requires that an airplane be able to survive a sudden pressure vessel failure.[7] Damage is allowed, but the airplane shall be able to continue flight and land. It also includes requirements to protect occupants from injury from debris that could be propelled by the decompression. As the rule text has evolved over the years it has introduced significant changes in hole sizes to be considered, treating the pressure differentials as limit or ultimate loads, etc. Earlier versions of the text as contained in 14 CFR 25 or JAR-25/CS-25 may be applicable via the Type Certification Basis to a particular airplane or modification thereto. The text of the current rule applicable to the purpose of this report is:

14 CFR/CS 25.365 Pressurized cabin loads.

(e)Any structure, component or part, inside or outside a pressurized compartment, the failure of which could interfere with continued safe flight and landing, must be designed to withstand the effects of a sudden release of pressure through an opening in any compartment at any operating altitude due to:

(1)Penetration from Engine Disintegration;

(2)Any opening up to:

$H_O = P\ A_S$, where,

H_O = Maximum opening, need not exceed 20 Sq Ft.

A_S = Maximum cross-sectional area of the pressurized shell Sq Ft; and

$P = (A_S / 6240) + 0.024$

(3)Any Opening Caused by Airplane or Equipment Failures Not Shown to be Extremely Improbable.

(f)In complying with paragraph (e) of this section, the fail-safe features of the design may be considered in determining the probability of failure or penetration and probable size of openings, provided that possible improper operation of closure devices and inadvertent door openings are also considered. Furthermore, the resulting differential pressure loads must be combined in a rational and conservative manner with 1 g level flight loads and any loads arising from emergency depressurization conditions. These loads may be considered as ultimate conditions; however, any deformations associated with these conditions must not interfere with continued safe flight and landing. The pressure relief provided by intercompartment venting may also be considered.

(g)Bulkheads, floors, and partitions in pressurized compartments for occupants must be designed to withstand the conditions specified in paragraph (e) of this section. In addition, reasonable design precautions must be taken to minimize the probability of parts becoming detached and injuring occupants while in their seats.

[Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-54, 45 FR 60172, Sept. 11, 1980; Amdt. 25-71, 55 FR 13477, April 10, 1990; Amdt. 25-72, 55 FR 29776, July 20, 1990, Amdt. 25-87, 61 FR 28695, June 5, 1996]

[7] Refer to US Federal Register preamble to the final rule for 14 CFR Part 25, Amendment 71, 55 FR 13477, April 10, 1990.

The interpretation provided in the US Federal Register preambles to the Final Rules for 14 CFR Part 25 Amendments 54 and 71 requires that the hole size per 14 CFR/CS 25.365(e)(2) shall be evaluated, even if there is no fuselage opening of this size because holes can result from detonation of bombs, corrosion and errors in maintenance, production and operation. The exception allowed is if the compartment is so small that the hole would overlap into the adjacent compartment. Then, evaluation is required of the largest opening that could occur without overlap. As a separate condition, the small compartment would then be combined with an adjacent pressurized compartment and both considered as a single compartment for the maximum size opening specified.

The rules require that holes from uncontained engine and APU rotor fragments be evaluated if any part of the pressure vessel is within the fragment trajectory. FAA AC 25-20 and AC 20-128A provide criteria for rotor fragment trajectory analysis for US certified airplanes. An entire window shall be assumed lost, if it is in the rotor non-containment zone. Current large transport airplanes with aft fuselage or wing-mounted engines generally have some portion of the pressure vessel within the engine rotor non-containment zone. Some small business jet airplanes with aft-mounted engines are able to place their pressure bulkhead entirely forward of the engine rotor non-containment zone, using the unpressurized tailcone space for baggage. Some others that have their aft pressure bulkhead within the rotor non-containment zone add a secondary aft pressure bulkhead. The volume between the primary and secondary aft pressure bulkheads is used for baggage and the secondary bulkhead is provided with fast acting shut-off valves to isolate the baggage compartment in case it is penetrated by an engine rotor fragment.

Other openings which should be evaluated include doors, windows, windshield, tire burst damage and openings resulting from airplane and equipment failures. 14 CFR/CS 25.783(b) require that door opening in flight shall be extremely improbable. However, 14 CFR §25.783(h) allows for door opening in flight if it can not cause a hazard. 14 CFR/CS 25.775(d) require that windows and windshields on airplanes approved for high altitude flight shall be of redundant structural design, such that sufficient strength remains to carry pressurization loads should a single pane fail. FAA AC 25-20 provides the additional criteria required to show that structurally redundant window and windshield installations also meet the Extremely Improbable criteria of 14 CFR §25.365(e)(3). EASA has not yet adopted FAA AC 25-20 and applies criteria in addition to those contained in FAA AC 25-20 for showing compliance with CS 25.365(e).

14 CFR/CS 25.775(b) and 25.571(e) prohibit windshield penetration from birdstrike. However, bird penetrations of windshields in excess of the regulatory requirements have occurred in service and (partial) windshield loss may therefore have to be considered for decompression in spite of compliance with 14 CFR/CS 25.775(b). Birdstrike can result in fuselage penetration as long as it does not cause hazard. 14 CFR/CS 25.571(a) and 25.729(f) prohibit hazard from a tire burst or loose tread, but do not prohibit penetration. Equipment failures (ducting, check valves, etc…) and airplane failures (loss of antennae, fatigue cracks, etc…) should be evaluated, if they can cause significant pressure differentials. However, equipment and airplane failures will also need to be evaluated for protection of occupants from hypoxic injury, which will generally result in more stringent criteria. Refer to Section 3.1.

If operating rules require the airplane be equipped with a flightdeck door, 14 CFR/CS 25.795 require the door installation to be resistant to intrusion and ballistic penetration. FAA memorandum dated November 6, 2001 provides criteria for decompression analysis of intrusion resistant flightdeck doors. [8] Freighters may not be required to have a secure flightdeck door if adequate ground security measures are provided.

3.3 Pressures In Adjacent External Compartments Due to Very Rapid Cabin Decompression

14 CFR/CS 25.365 require that the effects of sudden discharge of cabin pressure into normally unpressurized external compartments adjacent to the pressure vessel be evaluated. Sudden venting of cabin pressure into an external compartment that is not intended to carry significant pressure loads can cause hazard to the airplane by loss of structural integrity or damage to critical systems. Depending on the airplane configuration, these compartments may include tail surfaces, engine pylons, wing-fuselage fairings, wheel wells, radomes, fuel tanks, tailcone, nose compartment and baggage compartments.

Section 3.2 discusses causes of pressure vessel openings. Only those that vent into the adjoining compartments need be evaluated.

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[8] FAA Memorandum from Manager, Transport Airplane Directorate, ANM-100- Certification of Strengthened Flightdeck Doors on Transport Category Airplanes, Dated November 6, 2001, Revised December 3, 2002

3.4 Modifications to Previously Approved Airplanes

Any modifications to the airplane design should be approved in accordance with the requirements of the certification basis. Lengthening or shortening a fuselage to create a derivative airplane would have an obvious effect on decompression certification. Addition or relocation of pressure vessel openings has such an obvious impact on decompressions that the maximum allowable pressure vessel opening may be specified on the airplane Type Certification Data Sheet. [9]

Examples of other factors that are not as obvious are:

- Addition of equipment or furnishings that significantly change the compartment air volume or block existing decompression airflow paths. For example, a freighter conversion can greatly reduce cabin air volume, while a VIP conversion could significantly increase air volume.
- Change to stronger door latches or addition of items of mass on doors that are intended to open during a decompression and relieve loads on critical structure.
- Location of seating closer to a frangible partition.
- Repair or modification that increases the strength or stiffness of an external fairing adjacent to a pressure vessel that prevents it from deflecting during a decompression to relieve load from critical structure.

This brief list is intended only to show that the design intent related to prevention of hazard from decompressions may not be readily apparent.

4. DESIGN MEASURES

4.1 Design Measures for Protection of Occupants from Excessive Cabin Altitude

FAA, JAA and EASA rules and Special Conditions for airplanes approved for high altitude flight require that supplemental oxygen be readily available to all occupants. Passenger masks are required to deploy automatically and provide oxygen if cabin altitude exceeds 4572 m (15 000 ft) and flight crewmembers are required to be provided with quick-don masks that can be donned with one hand in less than 5 seconds. Availability of supplemental oxygen is not complete protection from hypoxia. Phase-diluter masks provided for passenger do not provide adequate protection above 12 192 m (40 000 ft) and provide protection for only limited durations above 7620 m (25 000 ft). Pressure-Demand crew masks do not provide adequate protection from rapid decompressions above 12 497 m (41 000 ft), unless oxygen is pre-breathed [10]. FAA operating rules require at least one flight crewmember to be using oxygen during high altitude flight, but there are no comparable requirements in EU OPS 1 or for international flight (ICAO).

Emergency descent alone, whether initiated by the crew or by an auto-descend system does not provide complete protection from rapid cabin decompression. An airplane may not exceed its maximum allowable airspeed during an emergency descent. High performance airplanes that can cruise at their max allowable airspeed may need to decelerate before they can initiate emergency descent. Use of emergency descent will generally be combined with other measures, such as limiting the size of potential pressure vessel leaks or use of a supplemental inflow system to limit the cabin climb rate.

[9] Refer to FAA Type Certification Data Sheet No. A1WI- "Any modifications to the pressure vessel must be approved in accordance with the requirements as shown in the certification basis. This includes modifications which could result in a pressure vessel opening, either through crack-growth or antenna loss, greater than 3.00 sq. in."

[10] For protection capabilities of supplemental oxygen equipment, refer to:
SAE AIR825/1- Introduction to Oxygen Equipment for Aircraft
SAE AIR825/8- Continuous Flow Oxygen Systems
SAE AIR825/9- Demand Oxygen Systems

An auto-descend system can bring an airplane down from altitude even if the crew is incapacitated. This is typically implemented by additional programming in the autopilot. When the autopilot receives signal of excessive cabin altitude (typically at 3048 m (10 000 ft)) it puts the airplane into a max rate descent, turns it from its flight path and levels off at an altitude that is safe for unpressurized flight. The reason for the change to flight path is that airplanes are controlled to flight lanes with traffic flying in the opposite direction at alternating flight levels. An auto-descend system may be able to exceed the performance of the crew in initiating an emergency descent, since it can act immediately on indication of excessive cabin altitude while reaction time testing of flight crews described in FAA AC 25-20 shows a 75th percentile reaction time of 17 seconds. However, the crew may not regain consciousness for several minutes if incapacitated by rapid decompression at high altitude [11]. The auto-descend system may not be able to equal crew performance if it can not be given authority over all required lift and drag devices (which may include landing gear) and the authority to execute maneuvers (such as a split-S to bleed off excess airspeed) as aggressively as the crew.

Warning of excessive cabin altitude is required by regulation before the cabin altitude reaches 3048 m (10 000 FPA). Cabin altitude warning is primarily of benefit for gradual decompressions, since rapid decompression is inherently detectable.

Airframe and system design measures which can limit cabin altitudes from decompression include:

Minimizing the size of every pressure vessel opening. For example, an antenna, stall vane or pitot mast may require a cutout through the pressure vessel that exceeds the allowable opening size. An internal pressure barrier (shroud) can be added inside the pressure vessel over the base of the component with an opening only large enough for the cable or hose connector.

Installing components on the inside of the pressure vessel, wherever possible. Pressure loads will hold the component against the pressure vessel opening should its attaching fasteners fail.

Providing structurally redundant attachments of components to the pressure vessel. Is an antenna installed with four bolts one attachment or four? Depending on guidance from the Certifying Authority, there may be no credit for use of multiple fasteners, especially if the location of the component makes all of the attachments vulnerable to the same environmental factors (such as corrosion of belly mounted antenna fasteners) or the same manufacturing or material defect. A dissimilar-redundant attachment can be considered and the ability of the backup attachment method to hold the component in place would need to be demonstrated.

Providing multiple door seals. If hazardous decompression can result from a door seal blowout or deflation, a secondary seal can be added behind it. If both seals require inflation pressure, each should use a separate pressure source, so that a single failure can not cause loss of both seals. Since loss of a single seal would not be immediately apparent, monitoring of pressure supplied to inflatable seals, direct visual inspection and/or periodic functional testing of each seal may be required to prevent latent failure of a single seal from going undetected.

Providing partitioned door seals. Placing partitions in the door seal will limit deflation of the seal to only a single damaged section. The spacing of the partitions would be defined by the pressure vessel leakage area allowable for decompressions.

Providing captive door seals with multiple sealing surfaces. The door-to-frame gap can be limited so that the seal can not extrude from the opening and the seal can be provided with multiple sealing surfaces so that a seal split at any one point will not cause a leak past the other sealing surface. This is similar to providing a secondary door seal, except that both seals are combined into a single component. Door seal failure might result in an increase in leakage, but less than if the seal extruded out the gap and departed the airplane. The ability of the seal to remain in place with maximum gap that would result from failure of a single door latch would have to be demonstrated. If the door is used on every flight, the seal would have to be inspectable during preflight to verify it has not fallen off of the door when the door was open.

[11] Discussion of the need for oxygen pre-breathing in order to prevent crew incapacitation from sudden decompression to pressure altitude above 12,497 m (41 000 ft) is provided in US Federal Register Vol. 51, No. 52, Pages 9432-9433, Tuesday, March 18, 1986, Docket No. 23243, Withdrawal of Notice of Proposed Rulemaking, “Pilot Oxygen Mask Requirements”.

Providing a secondary pressure bulkhead. If the airplane design allows it, a secondary pressure bulkhead can be installed to partition the cabin from a leak. This has been applied to several small airplanes with aft mounted engines where the aft part of the pressure vessel is in the engine rotor non-containment zone. The aft compartment is used for a pressurized and heated baggage compartment. In case of a leak in the aft compartment, fast-acting shut-off valves automatically close on detection of rising cabin altitude to isolate the compartment from the passenger cabin.

There are two approaches to design of a secondary aft pressure bulkhead. For airplanes that have located their outflow/safety valves in the aft compartment, malfunction of the isolation valve could cause cabin overpressurization. For this design, enough open area is left in the secondary aft pressure bulkhead so that the pressure drop through the secondary pressure bulkhead openings with the isolation valve closed will not exceed the maximum allowable differential pressure. The leakage area in the secondary pressure bulkhead should also be kept small enough that it is effective in limiting cabin decompression rate should there be a leak in the aft compartment. If the outflow/safety valves are located in the main cabin, isolation valve malfunction can not cause overpressurization and the secondary aft pressure bulkhead can be provided with minimal openings so that normal cabin pressure can be maintained once the isolation valve is closed.

Providing check valves at every Environmental Control System (ECS) penetration. If a pressurization duct outside the pressure vessel should fail, the check valve will close to prevent loss of cabin air through that pressure vessel penetration.

Providing isolation valves. If a pressure vessel opening requires bi-directional flow of air, a fast-acting shut off valve can be installed that can be manually or automatically operated. Automatic operation can act faster than manual, but inadvertent operation, if it presents a hazard should be prevented.

Minimizing the size of ECS penetrations. Latent failure of a check valve should be considered, unless provided with a monitoring system. Since latent failure of a check valve could be combined with loss of airflow from that source, the allowable size of the check valve and its elements will be defined by the allowable leak rate. For example, if one 10 cm (4 inch) diameter check valve would allow too large a hole, it could be split it into two separate 7.6 cm (3 inch) penetrations. If a two-petal check valve would create too large a hole from latent failure of a single flapper, four petals could be used.

Providing multiple and independent sources of inflow air. Separate inflow paths from each engine should be provided. If a single ECS pack is installed, which is typical on some smaller airplanes, a backup emergency pressurization system that routes engine bleed air directly to the pressure vessel can be provided. The emergency pressurization system should provide some conditioning or control of the air temperature, so that inadvertent operation of the system is not hazardous. APUs can provide pressurization air, but credit as a mitigation for loss of primary inflow sources can not be given for them unless they are qualified as Flight Essential and operable at high altitude. Electrically driven compressors offer some opportunity for increased redundancy, since a compressor could be driven from a generator on any engine.

Providing increased inflow air. Use of an emergency pressurization system in addition to the normal inflow can overcome a small leak. A large leak would require orders of magnitude increase in inflow to prevent decompression. It is not economical to size the engine compressors to provide enough airflow for the largest possible leak, because it penalizes engine performance and efficiency for normal operation for the life of the airplane.

Setting the Cabin Altitude Warning to a lower altitude. Regulations require warning of excessive cabin altitude before the cabin altitude exceeds 3048 m (10 000 ft). Reducing the cabin altitude warning setting enables the crew to begin the emergency descent at a lower altitude, which will reduce the peak cabin altitude and duration of the decompression. The cabin altitude warning should be set as low as can be allowed by the tolerances of the warning setting and normal operation of the cabin pressurization control system.

FAA, JAA and EASA rules require that it shall be improbable for the cabin pressure control system to depressurize the cabin above 4572 m (15 000 FPA). This is necessary, because the area of a fully open outflow valve is normally much larger than other openings and would cause an unacceptable rate of depressurization.

The possibility of latent failures should be considered. Proper function of systems that are not used in normal operation can not be verified in normal airplane operation. Periodic functional test of passenger oxygen masks, cabin altitude warning, check valves, isolation valves, emergency pressurization and cabin altitude limiting function of the cabin pressure control system is usually adequate to verify they will be available when needed. However, depending on system architecture and component reliabilities, preflight functional check may be required.

The possibility of common mode failures should be considered. A backup system should not be disabled by the same failure or environmental factor that can cause loss of the primary system. For example, the same loss of electrical power that causes loss of primary inflow should not also cause inability to activate an emergency pressurization system. Independence can be shown by architectural design, testing or system safety analysis. For any new or derivative airplane, system safety analysis will be required of all new or changed systems.

Approval of deferred maintenance or repairs should be considered. Dispatch with inoperative systems should be anticipated. Additional testing and analysis for abnormal operating conditions may be required. For example, will an operating altitude limitation be required for dispatch with:

Flaps or lift spoilers inoperative- affects ability to rapidly descend.

Emergency pressurization inoperative- affects ability to compensate for loss of primary inflow and ability to overcome a pressure vessel leak.

One bleed air source inoperative- affects ability to overcome a pressure vessel leak.

4.2 Design Measures to Prevent Loss of Structural Integrity from Cabin Pressure Venting

Components of internal and external compartments could be designed to withstand the peak pressure differentials that would result from sudden release of cabin pressure, but venting of the compartment reduces the pressure differential and allows for a lighter design. Venting can be provided by providing gaps between the outer edge of the floor and the fuselage skin, adding holes to frame webs of internal structure and leaving gaps around the edges or at the bottom of cabin partitions.

If openings are not allowed, such as in flightdeck doors, baggage liners and external aerodynamic surfaces, pressure relief panels can be provided. For small fuselage diameters, it may be possible to provide adequate pressure relief area with relief panels in the flightdeck door. For large fuselage diameter airplanes, the entire door can be used as the pressure relief panel for the flightdeck. If the flightdeck door is designed to open to relieve pressure differential across the partition, the controls or latches should allow the door to open from decompression, but not from intrusion attempt. Both pneumatic and electronic latch controls are in use.

Blowout doors have been used in cargo compartment liners. If a blowout panel could cause hazard by striking something, it should be restrained by hinges, lanyards or cages. An internal partition can be allowed to vent the pressure by folding over under load, but it should not be able to deflect so that it can hit an occupant.

An airplane with an unpressurized aft baggage compartment can use the baggage door as the relief panel for an aft pressure bulkhead failure, if the door latches can be designed to release at a low differential pressure. The door has much greater area than the size of the hole and does not need to open far to relieve the tailcone pressure.

EASA AMC 25.365(e) notes that a hazard assessment should determine which structures are required to withstand the resulting differential pressure loads. Secondary consequences of failures of these structures should address those events that have a reasonable probability of interfering with safe flight and landing. Secondary structure skin panels can be treated as “sacrificial”. The panel or its attachment can be designed so that it will depart the airplane at a low differential pressure, to relieve load and prevent hazardous damage to primary structure or critical systems mounted to the supporting structure. A typical application of this approach is with wing to fuselage fairings. Impact on the main structure from non critical structures, such as fairings, detached from the aircraft due to decompression need not be considered. However, allowing for loss of parts from the airplane should not create a greater hazard by hitting tail surfaces, or aft mounted engines. If separation of the part has a reasonable probability of interfering with safe flight and landing, it can be designed to stay attached and create an opening by lifting up at only one edge.

5. ESSENTIAL EQUATIONS:

Variable symbols used in this report are defined in TABLE 1. Values of constants and their symbols are defined in TABLE 2.

5.1 Atmospheric Pressure

Ambient pressure and temperature lapse rates are defined by mathematical models of a standard atmosphere. NACA Report 1235 provides equations and constants in both USCS and SI units for modeling of the variation of atmospheric pressure for altitudes up to 20 000 m (65 616.80 ft). This altitude is adequate for all civil airplanes, including the Concorde. NACA Report 1235 adopted the ICAO standard atmosphere and provided conversions from the SI primary units to U.S. Customary System (USCS) Foot-Pound units. Consequently, atmospheric properties calculated from NACA Report 1235 equations will match data provided in more current publications, such as for the U.S. and ISA Standard Atmospheres. The 1976 U.S. Standard Atmosphere provides data for higher altitudes, but only in SI units.

If different pressure units are desired in any of the altitude-pressure equations, make the following substitutions in TABLE 4:

TABLE 4- PRESSURE CONVERSIONS

USCS Equations	Replace 2116.216 lbf/ft^2	With 14.69595 lbf/in^2
		Or 29.92126 In Hg
SI Equations	Replace 101 325 Pa	With 101.325 kPa
		Or 760 mm Hg
		Or 1.013 250 Bar

Use of Inches of Water as a unit of pressure is strongly discouraged, because of the numerous standards existing for this unit.

5.1.1 Standard Atmosphere Up To 11 000.00 m (36 089.24 ft)

The relation for static air pressure variation with altitude is:

$$\frac{P}{P_0} = \left(\frac{T_0 - a \times H}{T_0}\right)^n \qquad \text{(Eq. 1)}$$

In USCS units, this relation is:

$$P = 2116.216 \times \left(1 - 6.87535 \times 10^{-6} \times H\right)^{5.25616} \quad , \quad lbf/ft^2 \qquad \text{(Eq. 2)}$$

In SI units, the relation is:

$$P = 101325 \times \left(1 - 2.25569 \times 10^{-5} \times H\right)^{5.25616} \quad , \quad Pa \qquad \text{(Eq. 3)}$$

The relation for pressure altitude as a function of static air pressure is:

$$H = \frac{T_0}{a} \times \left[1 - \left(\frac{P}{P_0}\right)^{1/n}\right] \qquad \text{(Eq. 4)}$$

In USCS units, this relation is:

$$H = 145447 \times \left[1 - \left(\frac{P}{2116.216}\right)^{0.190253}\right] \quad , \quad ft \qquad \text{(Eq. 5)}$$

In SI units, the relation is:

$$H = 44332.3 \times \left[1 - \left(\frac{P}{101325}\right)^{0.190253}\right] \quad , \quad m \qquad \text{(Eq. 6)}$$

5.1.2 Standard Atmosphere From 11 000.00 m to 20 000.00 m (36 089.24 ft to 65 616.80 ft)

The relation for static air pressure variation with altitude is:

$$Log\left(\frac{P}{P_0}\right) = n \times Log\left(\frac{T^*}{T_0}\right) - B \times (H - H^*) \qquad \text{(Eq. 7)}$$

In USCS units, this relation is:

$$P = 0.223356 \times 2116.216 \times e^{-0.0000480627 \times (H - 36089.24)} \quad , \quad lbf/ft^2 \qquad \text{(Eq. 8)}$$

In SI units, the relation is:

$$P = 0.223356 \times 101325 \times e^{-0.000157688 \times (H - 11000)} \quad , \quad Pa \qquad \text{(Eq. 9)}$$

The relation for pressure altitude as a function of static air pressure is:

$$H = H^* + \frac{1}{B} \times \left[n \times Log\left(\frac{T^*}{T_0}\right)\right] - \frac{1}{B} \times Log\left(\frac{P}{P_0}\right) \qquad \text{(Eq. 10)}$$

In USCS units, this relation is:

$$H = 36089.24 - 20806.2 \times Ln\left[4.47716 \times \left(\frac{P}{2116.216}\right)\right] \quad , \quad ft \qquad \text{(Eq. 11)}$$

In SI units, the relation is:

$$H = 11000 - 6341.64 \times Ln\left[4.47716 \times \left(\frac{P}{101325}\right)\right] \quad , \quad m \qquad \text{(Eq. 12)}$$

5.1.3 Ram Air Pressurization

During a rapid decompression from complete loss of inflow and subsequent emergency descent, cabin pressure will approach ambient pressure. If the airplane is equipped with a ram air fresh air ventilation system, the cabin pressure will be maintained at a differential equal to the aerodynamic dynamic pressure (q) minus ram inlet and ducting losses. The equation for compressible dynamic pressure is:

$$q = P_0 \times \left\{ \left[1 + \left(\frac{\gamma - 1}{2} \right) \times \left(\frac{V_C}{V_0} \right)^2 \right]^{\left(\frac{\gamma}{\gamma - 1} \right)} - 1 \right\}$$ [12] (Eq. 13)

Units for q in Equation 13 will be same units as used for P_0.

If a value of 1.40 can be used for γ, Equation 13 simplifies to:

$$q = P_0 \times \left\{ \left[1 + 0.2 \times \left(\frac{V_C}{V_0} \right)^2 \right]^{3.5} - 1 \right\} \quad \text{(Eq. 14)}$$

Units for q in Equation 14 will be the same units as used for P_0.

If airspeed is expressed as Mach number, the following relation can be derived from Equation 1B-62 in the section of AIR1168/1 titled "Pressure Ratio, Density, and Mach Number Relations":

$$q = P_s \times \left\{ \left[1 + \left(\frac{\gamma - 1}{2} \right) \times M^2 \right]^{\gamma / (\gamma - 1)} - 1 \right\} \quad \text{(Eq. 15)}$$

Units for q in Equation 15 will be the same units as used for P_s.

If a value of 1.40 can be used for γ, Equation 15 simplifies to:

$$q = P_s \times \left[\left(1 + 0.2 \times M^2 \right)^{3.5} - 1 \right] \quad \text{(Eq. 16)}$$

Units for q in Equation 16 will be the same units as used for P_s.

High performance airplanes will be limited at high altitudes to a maximum allowable Mach number (Mmo) and at low altitudes to a maximum allowable calibrated airspeed (Vmo), as illustrated in FIGURE 2 for an example of 0.75 Mmo and 290 KCAS Vmo.

[12] Derived from Equation 4.78 in Anderson [1978].

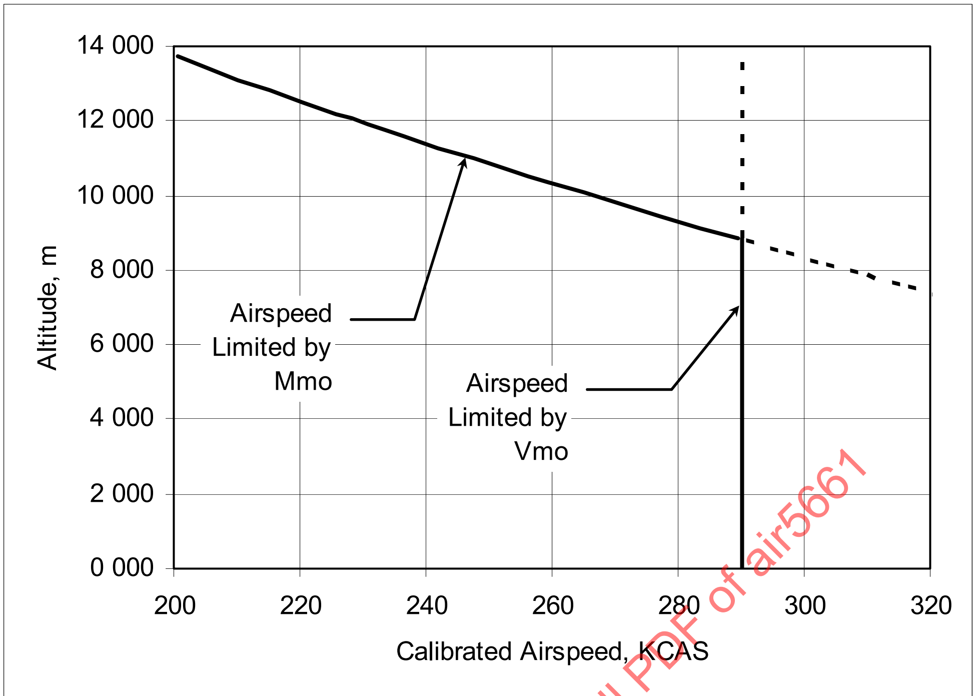

FIGURE 2- AIRSPEED LIMITATION CHART

The limiting calibrated airspeed will be the lesser of Vmo or the calibrated airspeed calculated from Mmo. Consequently, the available dynamic pressure will be the lesser of the values calculated from Vmo or Mmo. The ram air pressure available for cabin pressurization will be the dynamic pressure minus the inlet and ducting losses. A typical flush or recessed inlet will recover about 60% of the dynamic pressure while a pitot scoop will generally recover more than 90%.

5.1.4 Airplane Descent Profile

An airplane's maximum descent rate capability will vary with its maximum allowable airspeed and altitude. At high altitudes, the airspeed limitation is based on a limiting Mach number, while it is based on a calibrated or indicated airspeed at lower altitudes. Consequently, the theoretical descent profile model will have at least this one transition point. While a calculated descent rate may be the only data available for preliminary design, use of calculated maximum descent rates, based on descent at the maximum allowable Mach number and airspeed will be optimistic for decompression analysis, because flight test demonstration of descent capability will require the airplane be kept below the maximum allowable Mach number and airspeed.

For a given airplane, the descent profile will be independent of the cause of the decompression. Data from one emergency descent test can be used for analysis of all decompression scenarios. Flight test data at a high sample rate can be used directly as a look-up table with step changes in airplane altitude for each time interval, but the altitudes can also be interpolated between each point to avoid the step changes.

If use of a complete descent profile data set, which can be 1000 points or more is unwieldy, the profile could be approximated as a single average rate of descent, but it is more accurate to represent it as a series of constant rates between points of significant change in descent rate.

5.2 Flow of Air Through an Opening

The ideal or isentropic mass flow rate of air through an opening will be defined by the opening area, the air density and the pressure ratio across the opening. Separation, turbulence and friction will reduce the actual flow rate. Separation reduces the effective flow area while turbulence and friction require a greater pressure be applied to achieve a given flow rate. The ratio of the actual flow rate to the isentropic flow rate is defined as the discharge coefficient. The discharge coefficient can be considered a geometry factor for the opening.

The discharge coefficient assumes negligible approach velocity for the upstream air (plenum flow) and incompressible flow. The effect of a velocity upstream of the opening, as would occur if an orifice was installed in a duct, will be to reduce the energy that is required to accelerate the air to the throat velocity, resulting in a greater flow rate for a given pressure ratio. The approach velocity factor is typically calculated from the ratio of opening diameter to upstream duct diameter.

The effect of compressibility is that as the ratio of downstream to upstream pressure decreases, flow rate does not increase proportionately and becomes limited by the upstream pressure. Multiplying the last two factors times the discharge coefficient produces the flow coefficient, which is the overall correction factor from the calculation of ideal flow rate.

Air flow through a well designed nozzle or venturi stays attached to the device walls, rather than separated and turbulent. Nozzles and venturis have a well-defined throat area, which makes their behavior match theoretical predictions. For unchoked (subcritical) flow, where the ratio of downstream to upstream pressure is above the critical ratio, the flow rate will vary with both the upstream and downstream pressures. For choked (critical) flow, where the ratio of downstream to upstream pressure is below the critical pressure ratio (approximately 0.528 for room temperature air), the flow rate is completely independent of downstream pressure and will vary only with the upstream pressure. The effective flow area through a thin sharp-edged orifice occurs some distance downstream of the throat. The effective throat area of an orifice, and consequently the orifice discharge coefficient varies with diameter ratio, Pressure Ratio and Reynolds Number. This non-ideal behavior of orifices has been addressed by use of different discharge coefficients for different pressure ratios, or by use of an average discharge coefficient over the range of pressure ratios of interest.

Thick orifices behave like nozzles. The airflow reattaches to the hole bore downstream of the initial opening so that the effective area does not vary significantly with pressure ratio. There is no exact transition point for where a thick orifice can be treated like a nozzle. ESDU Paper 82009 Section 2 indicates that for compressible flow conditions the thickness to diameter range of between 0.1 and 1.0 may provide unstable flow and transition between attached and separated flow.

None of the recommendations for flow coefficients in the following sections are intended to replace test data of the actual flow paths. If test data is not available, conservative estimates should be used. Computational Fluid Dynamics (CFD) methods can also be used to determine flow coefficients for complex geometries where handbook data is not available.

Airflow through a hole in the fuselage will not be discharging to true ambient static pressure. Static pressure differentials in external compartments adjoining the pressure vessel will generally be small compared to the cabin pressure differential. Static pressure variations on fuselage surfaces exposed to external airflow are similarly small. The shape of the opening, whether dished inward from a penetration, or outward from a rupture, will also modify the local static pressure around the opening.

Ram effect of the airstream along the fuselage surface will also cause a significant backpressure on the discharging airflow which will reduce the outflow rate and resulting rate of compartment decompression.[13] This effect can be ignored if the same compartment can also discharge into unpressurized adjacent compartments with small static pressure differentials from ambient.

5.2.1 Nozzles and Venturis

5.2.1.1 Nozzle Critical Pressure Ratio

When the ratio of downstream pressure (P_d) to upstream pressure (P_u) is equal to or below the critical pressure ratio (r_c), the flow through an ideal nozzle or venturi will be choked (sonic at the throat). The location where P_d occurs is immediately downstream of the throat. For small diameter ratios with negligible approach velocity (plenum or reservoir flow conditions) r_c is:

$$r_c = \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)} \quad [14] \qquad \text{(Eq. 17)}$$

For room temperature air (γ = 1.40), the critical pressure ratio r_c = 0.52828.

[13] Refer to NASA CR-61241.

[14] Kent's Handbook.

5.2.1.2 Nozzle Critical Flow Conditions

Flow through a nozzle or venturi will be choked when:

$$\frac{P_d}{P_u} \le r_c \quad \text{(Eq. 18)}$$

From Eq. 17, a nozzle or venturi will be choked when:

$$P_u = P_d \times \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \quad \text{(Eq. 19)}$$

It will also be choked at any higher upstream pressure when:

$$P_u \ge P_d \times \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} = P_d \times \left(\frac{2}{\gamma+1}\right)^{-\gamma/(\gamma-1)} \quad \text{(Eq. 20)}$$

5.2.1.3 Nozzle Choked Flow

For choked (sonic) flow through an ideal nozzle, the gravimetric mass flow rate will be:

$$\dot{w} = C_D \times A \times P_u \times \sqrt{\left(\frac{2 \times g_c}{R_a \times T_u}\right) \times \left(\frac{\gamma}{\gamma+1}\right) \times \left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)}} \text{ [15]} \quad \text{(Eq. 21)}$$

If a constant value of 1.40 can be used for γ, the following equation results:

$$\dot{w} = \frac{0.5309 \times C_D \times A \times P_u}{\sqrt{T_u}} \quad , \quad \text{lb/s} \quad \text{(Eq. 22)}$$

Equation 22 can also be used with the units of in^2 for area and lbf/in^2 for pressure. When the SI units of cm^2 for area and kPa for pressure are used, the equation is:

$$\dot{w} = \frac{0.004042 \times C_D \times A \times P_u}{\sqrt{T_u}} \quad , \quad \text{kg/s} \quad \text{(Eq. 23)}$$

5.2.1.4 Nozzle Non-Choked Flow

Kent's Handbook provides the following ideal non-choked nozzle gravimetric mass flow rate equations. Variable names have been changed to match nomenclature of this report:

$$\dot{w} = \sqrt{\frac{2 \times g_c}{R_a \times T_u}} \times \frac{1}{\sqrt{1-\beta^4}} \times A \times \phi \times \sqrt{P_u \times (P_u - P_d)} \quad \text{(Eq. 24)}$$

[15] Kent's Handbook.

$$\phi = \left\{ \frac{\frac{\gamma}{\gamma - 1} \times r^{(2/\gamma)} \times \left[1 - r^{(\gamma-1)/\gamma} \right]}{1 - r} \right\}^{1/2} \times \left(\frac{1 - \beta^4}{1 - \beta^4 \times r^{(2/\gamma)}} \right)^{1/2} \quad \text{(Eq. 25)}$$

$$\beta = \frac{D_d}{D_u} \quad \text{(Eq. 26)}$$

$$r = \frac{P_d}{P_u} \quad \text{(Eq. 27)}$$

Equation 24 was derived based on purely theoretical considerations. It is multiplied by the discharge coefficient to provide a relation for actual flow rate. Simplifying and rearranging:

$$\dot{w} = C_D \times A \times P_u \times \sqrt{\frac{2 \times \gamma \times g_c}{(\gamma - 1) \times R_a \times T_u}} \times \sqrt{\frac{r^{(2/\gamma)} - r^{(\gamma+1)/\gamma}}{1 - \beta^4 \times r^{(2/\gamma)}}} \quad \text{(Eq. 28)}$$

Equation 28 can be solved for C_D or A, but not for P_u or P_d. If a constant value of 1.40 can be used for γ, the following equation results:

$$\dot{w} = \frac{2.055 \times C_D \times A \times P_u}{\sqrt{T_u}} \times \sqrt{\frac{r^{(2/1.4)} - r^{(2.4/1.4)}}{1 - \beta^4 \times r^{(2/1.4)}}} \quad , \quad \text{lb/s} \quad \text{(Eq. 29)}$$

Equation 29 can also be used with the units of in^2 for area and lbf/in^2 for pressure. When the SI units of cm^2 for area and kPa for pressure are used, the equation is:

$$\dot{w} = \frac{0.01562 \times C_D \times A \times P_u}{\sqrt{T_u}} \times \sqrt{\frac{r^{(2/1.4)} - r^{(2.4/1.4)}}{1 - \beta^4 \times r^{(2/1.4)}}} \quad , \quad \text{kg/s} \quad \text{(Eq. 30)}$$

For small diameter ratios (plenum or reservoir flow conditions) Equation 28 simplifies to:

$$\dot{w} = C \times A \times P_u \times \sqrt{\frac{2 \times \gamma \times g_c}{(\gamma - 1) \times R_a \times T_u}} \times \sqrt{r^{(2/\gamma)} - r^{(\gamma+1)/\gamma}} \quad \text{(Eq. 31)}$$

If a constant value of 1.40 can be used for γ, the following equation results:

$$\dot{w} = \frac{2.055 \times C_D \times A \times P_u}{\sqrt{T_u}} \times \sqrt{r^{(2/1.4)} - r^{(2.4/1.4)}} \quad , \quad \text{lb/s} \quad \text{(Eq. 32)}$$

Equation 32 can also be used with the units of in^2 for area and lbf/in^2 for pressure. When the SI units of cm^2 for area and kPa for pressure are used, the equation is:

$$\dot{w} = \frac{0.01562 \times C_D \times A \times P_u}{\sqrt{T_u}} \times \sqrt{r^{(2/1.4)} - r^{(2.4/1.4)}} \quad , \quad \text{kg/s} \quad \text{(Eq. 33)}$$

5.2.1.5 Nozzle Discharge Coefficients

Kent's Handbook recommends the following discharge coefficients for several common nozzle geometries. These are shown in TABLE 5.

TABLE 5- NOZZLE DISCHARGE COEFFICIENTS

Nozzle Shape	C_D
Short Cylindrical Mouthpiece	0.81 to 0.84
Short Cylindrical Mouthpiece, Rounded at Inner End	0.92 to 0.93
Conical Converging Mouthpiece	0.90 to 0.99
Polished, Well Rounded Nozzle	0.938 to 0.995

These nozzle geometries are illustrated in FIGURE 3.

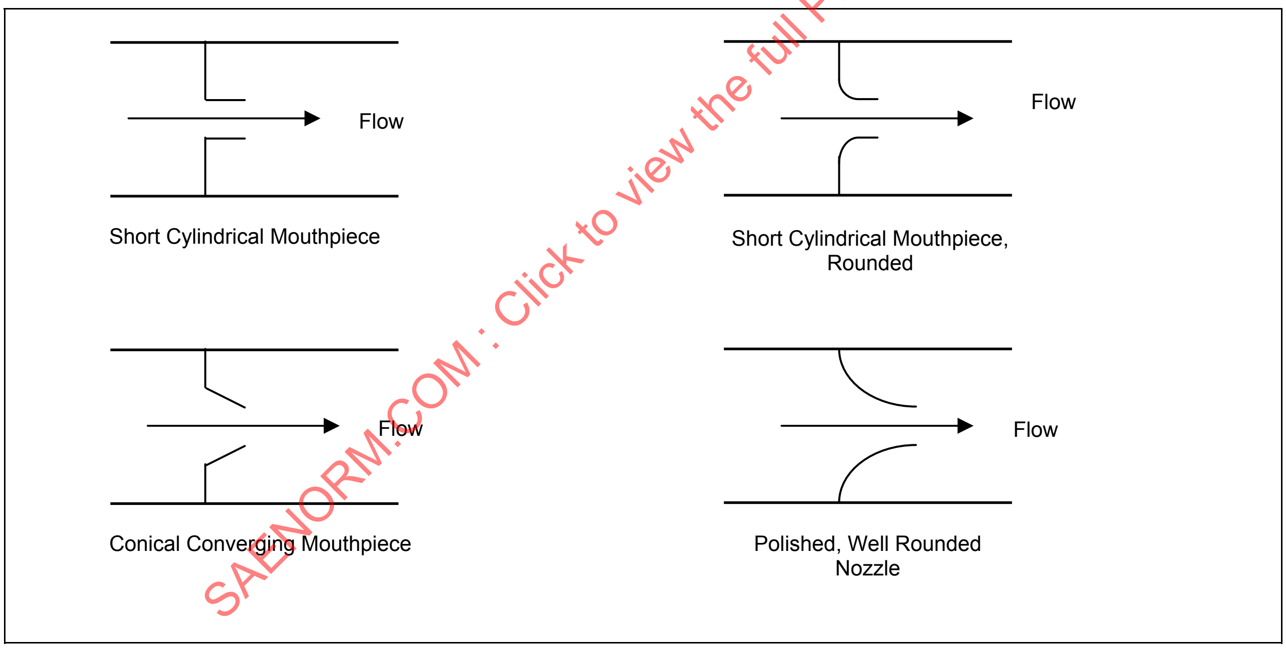

FIGURE 3- TYPICAL NOZZLE GEOMETRIES

5.2.1.6 Total Pressure Recovery Downstream of Nozzles and Venturis

A venturi consists of a convergent section, a throat and a divergent section. The purpose of the divergent section is to minimize pressure loss downstream of the throat. Total pressure loss from a smooth, rounded convergent section and throat will be small. Total Pressure remaining at the divergent section exit can be calculated from the pressure loss factor for a conical round diffuser.

A nozzle consists of only the convergent and throat sections. Pressure drop from a nozzle will be the sum of the pressure drop from the convergent section plus the pressure drop for a sudden increase in duct cross section.

Pressure downstream of a nozzle or venturi will need to be known only for situations where venting occurs through ducting containing these components.

5.2.2 Orifices

Orifice flow can be calculated using the theoretical-expansion-factor and critical-pressure-ratio flow equations from Section 5.2.1 with additional relations for a variable flow coefficient, or by defining a constant flow coefficient with an orifice flow compressibility factor. The following examples will show how these two methods give essentially the same result.

5.2.2.1 Orifice Flow Rate Using a Variable Discharge Coefficient

The nozzle flow equations from Section 5.2.1 can be used with orifices and other geometries if the variation of discharge coefficient with pressure ratio is determined by testing. Data for the discharge coefficient of a round orifice with zero approach velocity is provided by NASA TM X-53734. This data is plotted in FIGURE 4.

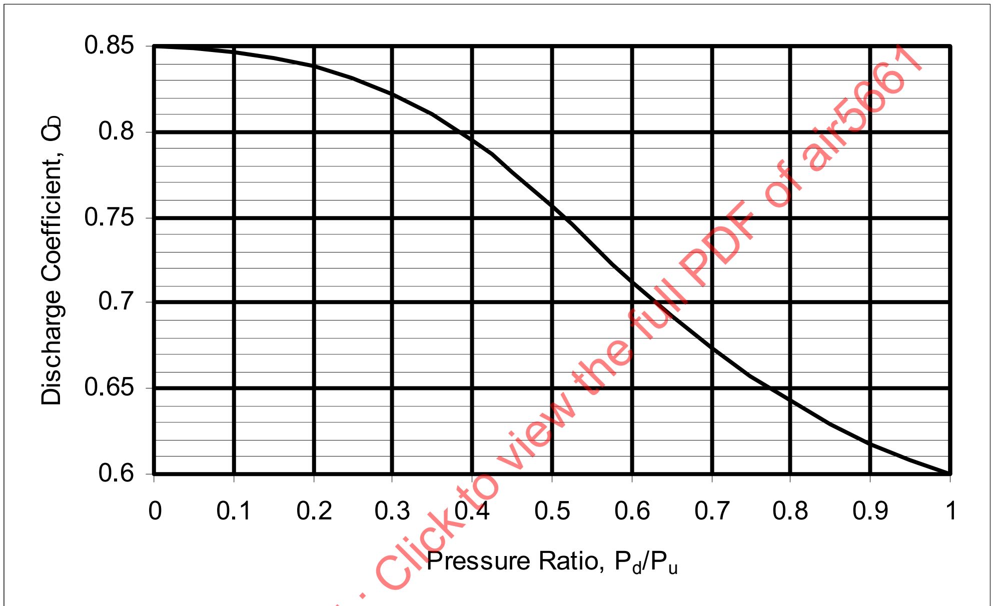

FIGURE 4- DISCHARGE COEFFICIENT FOR AIR FLOW THROUGH AN ORIFICE WITH ZERO APPROACH (PLENUM) VELOCITY

Data points taken from this curve are shown in Table 6.

TABLE 6- ORIFICE DISCHARGE COEFFICIENT DATA FROM FIGURE 4

P_d/P_u	C_D
1.0	0.600
0.90	0.618
0.80	0.643
0.70	0.674
0.60	0.712
0.50	0.757
0.40	0.795
0.30	0.8215
0.20	0.838
0.10	0.847
0	0.850

Curve fitting this data provides the following relation:

$$C_D = 0.84839 + 0.067878 \times r - 0.55538 \times r^2 - 0.045940 \times r^3 + 0.28700 \times r^4 \qquad \text{(Eq. 34)}$$

This discharge coefficient is used in the nozzle flow equations of Section 5.2.1.

This data is applicable only to round sharp-edged orifices. Data presented in NASA TM X-53734 for a square orifice shows its discharge coefficient to be slightly higher than for a round orifice. Discharge coefficient data for a rectangular orifice with width to height ratio of 4 overlaps the range of discharge coefficients for round orifices.

This method can be used to define discharge coefficient functions for other opening geometries from test data. The discharge coefficient is calculated as the ratio of the measured flow rate to the calculated flow rate for a nozzle of the same diameter at the same pressure ratio.

5.2.2.2 Orifice Flow Rate Using a Constant Discharge Coefficient

Orifice flow calculated with this method uses a discharge coefficient that is constant with respect to pressure ratio. Due to the lack of a distinct transition from unchoked to choked flow, a single flow equation with an ASME empirically derived compressibility factor is used for all pressure ratios.

$$\dot{w} = P_u \times A \times \frac{C_D}{\sqrt{1-\beta^4}} \times Y \times \sqrt{\frac{2 \times g_c}{R_a \times T_u} \times \left[1 - \left(\frac{P_d}{P_u}\right)\right]} \qquad \text{(Eq. 35)}$$

[16]

The expansion factor, Y is determined from the following equation, which is based on experimental data:

$$Y = 1 - \frac{\left(0.41 + 0.35 \times \beta^4\right) \times \left(P_u - P_d\right)}{P_u \times \gamma} \qquad \text{(Eq. 36)}$$

[17]

[16] SAE AIR1168/5, pg 45, Fig 3G-37 “Flow Factors for Orifices”.

[17] SAE AIR1168/5, pg 42, Section 4.2.2 “Calculation Procedure”.

AIR1168/5 provides several tables of orifice Flow Coefficient data. Over the extreme range of data provided for small diameter ratios, the average C_D is 0.60 and the extreme variation is less than +/-2%. If the orifice geometry is different from a sharp edged orifice, a different value for C_D should be used.

For small diameter ratios (plenum or reservoir flow conditions), Equation 35 simplifies to:

$$\dot{w} = P_u \times A \times C_D \times \left(1 - \frac{0.41 \times (P_u - P_d)}{P_u \times \gamma}\right) \times \sqrt{\frac{2 \times g_c}{R_a \times T_u} \times \left[1 - \left(\frac{P_d}{P_u}\right)\right]} \qquad \text{(Eq. 37)}$$

If a constant value of 1.40 can be used for γ, the following equation for small diameter ratios results:

$$\dot{w} = 1.098 \times P_u \times A \times C_D \times \left(1 - \frac{0.2929 \times (P_u - P_d)}{P_u}\right) \times \sqrt{\frac{1}{T_u} \times \left[1 - \left(\frac{P_d}{P_u}\right)\right]} \quad , \ \text{lb/s} \qquad \text{(Eq. 38)}$$

Equation 38 can also be used with the units of in^2 for area and lbf/in^2 for pressure. When the SI units of cm^2 for area and kPa for pressure are used, the equation is:

$$\dot{w} = 0.008347 \times P_u \times A \times C_D \times \left(1 - \frac{0.2929 \times (P_u - P_d)}{P_u}\right) \times \sqrt{\frac{1}{T_u} \times \left[1 - \left(\frac{P_d}{P_u}\right)\right]} \quad , \ \text{kg/s} \qquad \text{(Eq. 39)}$$

These equations can not be solved for explicit solutions for P_u or P_d.

5.2.3 Comparison of Orifice and Nozzle Flow Factors

The following example illustrates the different flow characteristics of orifices and nozzles/venturis. For the same throat area, an orifice will flow less than a nozzle or venturi. Both orifice flow calculation methods result in nearly the same required throat area for a given set of flow conditions. The manner in which the flow varies with pressure ratio is illustrated in FIGURE 5.

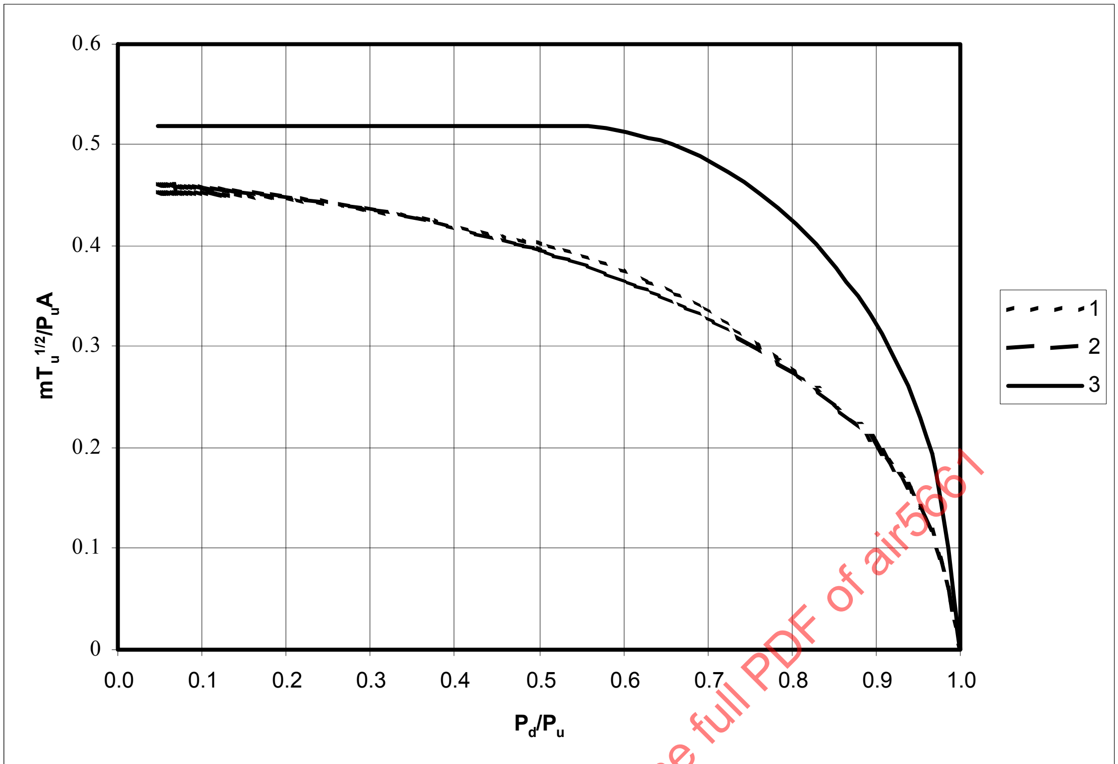

FIGURE 5- ORIFICE AND NOZZLE FLOW FACTOR COMPARISON

FIGURE 5 Legend:

1. Orifice, Theoretical-Expansion-Factor and Critical-Pressure-Ratio equations with Variable C_D (See 5.2.2.1)
2. Orifice, ASME Empirical-Expansion-Factor and Critical-Pressure-Ratio equations with Constant C_D (See 5.2.2.2)
3. Nozzle, Theoretical-Expansion-Factor and Critical-Pressure-Ratio equations (See 5.2.1)

The nozzle flow factor curve shows the classic theoretical behavior of a constant normalized flow factor below the critical-pressure-ratio (0.52828 for room temperature air). Both orifice flow calculation methods show essentially the same variation of flow factor with pressure ratio and the lack of a critical-pressure-ratio effect.

5.2.4 Flow of Air Through Valves

Gate valves and variable orifice (iris) valves can be modeled as a thin sharp orifice. Many other valves (poppet and butterfly) can be modeled as nozzles or thick orifices using the nozzle flow equations from 5.2.1, because of the relative length of the flow path compared to the size of the flow opening.

5.2.4.1 Butterfly Valves

A butterfly valve can be modeled as a thick orifice where the area varies with butterfly angle. Effective CA value will vary from the full open value to zero by the following relation:

$$C_\theta = [1 - \mathrm{Cos}(\theta)] \tag{Eq. 40}$$

where θ is 0 when the valve is fully closed. Full open flow coefficient can be estimated from the blockage of the duct area by the edgewise aspect of the butterfly:

$$C_B = \frac{(A - D \times x_b)}{A} \tag{Eq. 41}$$

Since butterfly valve characteristics can be expected to scale with size, the butterfly thickness can be represented as a ratio to the duct diameter:

$$r_b = \frac{Th}{D} \tag{Eq. 42}$$

Since:

$$A = \frac{\pi \times D^2}{4} \tag{Eq. 43}$$

Equation 41 will simplify to:

$$C_B = \left(1 - \frac{4 \times r_b}{\pi}\right) \tag{Eq. 44}$$

Combining the butterfly thickness blockage factor with the butterfly angle blockage factor:

$$C_{BF} = C_\theta \times C_B = [1 - \mathrm{Cos}(\theta)] \times \left(1 - \frac{4 \times r_b}{\pi}\right) \tag{Eq. 45}$$

If the response characteristics of the valve are undefined, the rate of closing can be assumed linear. If the time required for the valve to travel 90° from full open to full closed is t_c, the valve flow coefficient at any time between zero and t_c with the valve initially full open will be:

$$C_{BF} = C_\theta \times C_B = \left[1 - \mathrm{Cos}\left(\frac{t \times 90}{t_c}\right)\right] \times \left(1 - \frac{4 \times r_b}{\pi}\right) \tag{Eq. 46}$$

If the valve starts from a partially closed position (θ_i), the valve flow coefficient at any time (t) will be:

$$C_{BF} = \left[1 - \mathrm{Cos}\left(\theta_i + \frac{t \times 90}{t_c}\right)\right] \times \left(1 - \frac{4 \times r_b}{\pi}\right) \tag{Eq. 47}$$

where t will vary between zero and:

$$t_c \times \left(1 - \frac{\theta_i}{90}\right) \tag{Eq. 48}$$

5.2.4.2 General Valve Model

If the accuracy of the analysis does not require detailed modeling of the valve flow characteristics, a valve can be modeled as a nozzle with a CA that varies between zero and a maximum value linearly with time. If the valve requires time t_c to travel from full open to full closed, its effective area (CA) at any time between zero and t_c will be:

$$CA = CA_o \times \left(1 - \frac{t}{t_c}\right) \quad \text{(Eq. 49)}$$

If the valve is opening, instead of closing, the effective area at any time between zero and t_o (which can be a different time than t_c) will be:

$$CA = CA_o \times \left(\frac{t}{t_o}\right) \quad \text{(Eq. 50)}$$

If the valve starts from a partially closed position such that the initial effective area is CA_p, the valve flow coefficient at any time will be:

$$CA = CA_p \times \left[1 - \left(\frac{t}{t_c} \times \frac{CA_o}{CA_p}\right)\right] \quad \text{(Eq. 51)}$$

where t will vary between zero and:

$$t_c \times \frac{CA_p}{CA_0} \quad \text{(Eq. 52)}$$

5.2.5 Flow Coefficients for Other Openings

FAA AC 25-20 provides an acceptable means of compliance with FAA regulations pertaining to cabin decompression. Section 8.f. of that advisory circular states "In calculating the cabin altitude decompression profile, unless a different value can be established by a rational analysis acceptable to the FAA, an orifice discharge coefficient of C_d = 0.75 for loss of a window and C_d = 0.5 for a hole resulting from a fuselage damage should be assumed." These values are consistent with data for these types of openings. A window loss will result in an opening that includes the rounded window escutcheon. A window area of 0.102 m^2 (1.1 ft^2) would be equivalent to a circle with a diameter of 0.36 m (14.2 in). If the total depth of the fuselage frame and interior is 0.10 m (4 in) the ratio of opening depth to diameter will be 0.28, so a window loss will still result in a "thin" opening. Data presented by Miller [1996] Chapter 10, pg. 10.39 shows a discharge coefficient of 0.73 for a thin orifice with a chamfer equal to 8.4% of the orifice diameter and a discharge coefficient varying between 0.774 and 0.845 over the β range of from 0.25 to 0.6 for a thin orifice with a rounded inlet.

The causes of fuselage damage include fatigue cracks, engine fragment penetrations and antenna loss. The shapes of these openings will usually not be round or even. While rounding the corner of an orifice in the flow direction will increase the flow coefficient, rounding or forming the opening against the direction of flow, such as could occur from a penetration into the pressure vessel can be expected to reduce the flow coefficient below the typical value of 0.60 for a sharp round orifice.

In addition to the specific references provided for flow coefficient data elsewhere in this report, flow characteristics of openings with shapes other than nozzles and sharp-edged round orifices are available from the sources in the following sections. Flow coefficient functions can be calculated from test data using the theoretical expansion factor and critical pressure ratio flow equations from Section 5.2.1. The flow coefficient is calculated as the ratio of the measured flow rate to the calculated flow rate for a nozzle of the same diameter at the same pressure ratio.

While it is conservative to assume that openings occur instantaneously, data and analysis is available that accounts for the mass and opening geometry variation of vent panels. Veldman [2001] documents lab testing to predict fuselage decompression rates from deliberate openings. A small explosion that by itself does minor structural damage can still result in catastrophic damage if it sufficiently reduces the pressure vessel's ability to carry pressurization loads. The goal of this research was to devise a method to decompress the fuselage rapidly enough to prevent pressurization loads from propagating damage from an explosion. The testing included hinged panels and blow-out panels of significant mass and fracturing of a glass window. The test results matched closely with analytical predictions, except that as would be expected a fractured window resulted in a slightly higher rate of decompression than predicted for a blow out panel of the same mass and area. Since the analytical models predicted only the variation of the effective area during vent panel opening, the testing also shows that while the shape of the opening changes considerably during the initial phase of a vent panel opening any variation in discharge coefficient has a relatively small effect on decompression rates.

This research also evaluated the assumption of uniform pressure throughout the compartment during a Very Rapid Decompression by measuring the decompression time immediately adjacent to the opening and at several other locations in the pressure tank. The testing showed slightly higher variation in decompression times when measured adjacent to the opening, but no significant difference in the average times regardless of the location of the measurement.

5.2.5.1 SAE Flow Coefficient Data Reports

AIR1168/5 Discharge coefficient data for orifices and nozzles.

AIR1168/6 Effective area vs travel for louvers, butterfly and gate valves.

5.2.5.2 NACA Flow Coefficient Data Reports

WR-L-23 Pressure drop test data for wire mesh screens at air velocities up to choking.

Report 933 Flow Coefficient test data for conical nozzles with diameter ratios from 0.5 to 0.91 at pressure ratios from 1.0 to 2.8.

TN 1947 Orifice coefficient test data for circular, elliptical and square orifice jets directed perpendicular to airstream.

TN 3359 Flow coefficient and liquid discharge test data for fourteen types of drain masts discharging into an airstream velocity of Mach 0.5 to 1.3.

TN 3466 Discharge coefficient test data for a wide variety of flush and recessed outlets discharging into an airstream velocity of Mach 0.7 to 1.3.

TN 3924 Discharge coefficient test data for wide variety of holes, slots, scoops and louvers with air flow across the surface.

5.2.5.3 NASA Flow Coefficient Data Reports

CR-61241 Discharge coefficient test data for circular, elliptical, square and rectangular orifices discharging into an airstream velocity of M 0.7 to M 1.9

TM X-53734 Discharge coefficient test data for circular, square and rectangular orifices and skin lap gaps

5.2.5.4 Other Flow Coefficient Data Sources

Miller [1996] Discharge coefficient data for orifices (sharp, rounded, thick, thin, concentric, eccentric and segmented), nozzles and venturis.

5.3 Compartment Effective Air Volume

For analysis of rapid decompression or depressurization where the object is to determine the pressure altitude-time history of an occupied compartment (such as for showing compliance to 14 CFR §25.841(a)), the configuration and loading of the airplane that provides the lowest air volume in the compartment should be used. The gross internal volume should be reduced by the volumes of structure, equipment, furnishings and occupants. If the component is irregular such that calculation or measurement of its solid volume is difficult, the solid volume can be estimated from the component weight and material density. If the component is hollow but not deliberately ventilated, it may be necessary to subtract the entire envelope of the part. Similarly, if it is difficult to determine the solid portion of a hollow and ventilated component, it is conservative to subtract the volume of the entire component envelope.

Since the size of occupants can be expected to vary with the population, it is reasonable to use the average of the 50th percentile adult male and female body volumes. Data from NASA-STD-3000 shows an average occupant will displace approximately 0.07 m^3 (2.5 ft^3).

For analysis of Very Rapid Decompressions where the goal is to determine peak pressure differentials across pressure barriers, using the maximum volume of the compartment from where the air is discharging and the minimum volume of the compartment being discharged into will result in the greatest pressure differential loads. However, as decompression loads have to be combined with 1-g level flight loads (ref. 14 CFR/CS 25.365(f)) the effect of compartment volume needs to be carefully examined. For example, an occupied (discharging) cabin compartment would contain less air volume, and hence result in lower pressure loads over the cabin or cargo floor in case of a lower lobe blow-out, but the effect of the downward acting 1-g load from seats, occupants and/or cargo have to be added which may result in the determining load case.

5.4 Compartment Rate of Air Mass and Pressure Change

5.4.1 Ideal Gas Law

At any moment, the weight of air in a compartment can be determined from the ideal gas law:

$$w = \frac{P \times V}{R_a \times T} \qquad \text{(Eq. 53)}$$

as can the air pressure and density:

$$P = \frac{w \times R_a \times T}{V} \qquad \text{(Eq. 54)}$$

$$\delta = \frac{w}{V} \qquad \text{(Eq. 55)}$$

The presence of water vapor in the air will reduce the air density, but the difference is small at high humidity levels and negligible at the low cabin air humidities that are present for the majority of the flight time.

If air flows into or out of the compartment, the instantaneous rate of pressure change will be:

$$\frac{dP}{dt} = \frac{dw}{dt} \times \frac{R_a \times T}{V} \qquad \text{(Eq. 56)}$$

If air is both flowing into and out of the compartment:

$$\frac{dP}{dt} = \left(\dot{w}_{in} - \dot{w}_{out}\right) \times \frac{R_a \times T}{V} \qquad \text{(Eq. 57)}$$

The mass of air in a compartment (w_2) after an interval of time (dt) will be the initial mass (w_1) plus the net rate of flow into or out of the compartment times the time interval (dt):

$$w_2 = w_1 + \left(\dot{w}_{in} - \dot{w}_{out} \right) \times dt \quad \text{(Eq. 58)}$$

It also follows that the compartment air density (δ_2) after a time interval dt will be:

$$\delta_2 = \frac{w_1 + \left(\dot{w}_{in} - \dot{w}_{out} \right) \times dt}{V} \quad \text{(Eq. 59)}$$

These relations can not be used to directly calculate the final air mass and density if the rates of air inflow or outflow vary during the time increment. If the relations that define the variable rates of air inflow and outflow are relatively simple, these equations can be integrated over the time interval. If the airflow rate relations are too complex to allow a direct solution, a step-wise calculation can be performed, with the airflow rates recalculated after each time interval. If the time interval is kept small, a step-wise calculation will be sufficiently accurate for practical purposes. The equation for step-wise calculation of the final compartment air weight for n steps will be:

$$w_2 = w_1 + \sum_{1}^{n} \left(\dot{w}_{in} - \dot{w}_{out} \right) \times \Delta t \quad \text{(Eq. 60)}$$

where the time increment (Δt) is:

$$\Delta t = \frac{t}{n} \quad \text{(Eq. 61)}$$

5.4.2 Isothermal Process

An isothermal process is one in which the temperature remains constant. SAE AIR1168/7 Section 4 "Emergency Release of Cabin Pressure" notes that air temperature can be assumed to remain constant during a decompression, due to heat transfer from cabin surfaces and the relatively long pressure decay time. The purpose of SAE AIR1168/7 Section 4 is to provide a means to determine the time required for deliberate depressurization for smoke evacuation or rapid evacuation of military aircraft. FAA AC 25-22, Section 25.841 notes that a depressurization time of two minutes or less is typical in large transport aircraft. This time for a deliberate depressurization is comparable to the duration of an inadvertent decompression due to complete loss of pressurization inflow air, pressurization control system failures, loss of antennae or other fittings to cause leaks from the pressure vessel.

If the decompression scenario results in no loss or only partial loss of inflow air, the cabin temperature control system may be able to compensate for any gradual decrease in cabin air temperature. Cabin decompressions from complete loss of inflow with no other failure to cause an increase in pressure vessel leakage tend to be more gradual than deliberate depressurizations or decompressions from large pressure vessel leaks. The loss of inflow air for heating is offset by the somewhat longer pressure decay time and the greater heat transfer from cabin surfaces.

If compartment air temperature is constant, the pressure change will be directly proportional to the compartment air mass change. Consequently, for a given change in compartment air mass:

$$P_1 - P_2 = \left(w_1 - w_2 \right) \times \frac{R_a \times T}{V} \quad \text{(Eq. 62)}$$

This relation will apply regardless of the rates of air inflow and outflow during the pressure change, since it merely relates the initial and final states. Combining Equations 58 and 62 and simplifying:

$$P_2 = P_1 + dt \times \left(\dot{w}_{in} - \dot{w}_{out}\right) \times \frac{R_a \times T}{V} \qquad \text{(Eq. 63)}$$

Equation 63 can not be used to directly calculate the final air pressure if the rates of air inflow and outflow vary during the time increment. If the inflow and outflow rates vary over the time interval, the equations that define their variation are inserted into Equation 63 and the resulting relation is integrated to find the final compartment air pressure. If the airflow rate relations are too complex to allow a direct solution, a step-wise calculation can be performed, with the airflow rates recalculated after each time interval. If the time interval is kept small, a step-wise calculation will be sufficiently accurate for practical purposes.

The SAE AIR1168/7 Section 4 equation for the time for pressure to decay when flow through the exit is supercritical (choked) at both the initial and final pressures is repeated here with variable symbols and units changed to match other sections of this report.

$$t' = \frac{V \times \delta_1}{\dot{w}_{out1}} \times Ln\left(\frac{\dot{w}_{out1} - \dot{w}_{in}}{\dot{w}_{out2} - \dot{w}_{in}}\right) \quad , \text{ seconds} \qquad \text{(Eq. 64)}$$

As long as consistent units are used, Equation 64 applies to both SI & USCS units, since all units of mass and volume cancel. The air mass flow rates in Equation 64 at any instant are defined by the choked flow equation from Section 5.2.1.3, which assumes a constant flow coefficient. If the outlet flow coefficient varies with the pressure ratio, the appropriate flow coefficient value for the initial and final pressure ratios can be used since both pressures are specified.

Derivation of Equation 64 from ideal gas law relations is demonstrated here. Rearranging Equation 57 from Section 5.4.1:

$$dt = \frac{V}{R_a \times T} \times \frac{1}{\left(\dot{w}_{in} - \dot{w}_{out}\right)} \times dP \quad , \text{ seconds} \qquad \text{(Eq. 65)}$$

$$\int_0^{t'} dt = \frac{V}{R_a \times T} \times \int_{P_1}^{P_2} \frac{1}{\left(\dot{w}_{in} - \dot{w}_{out}\right)} dP \qquad \text{(Eq. 66)}$$

Substituting Equation 22 from Section 5.2.1.3 for $\dot{w}_{out}$:

$$\int_0^{t'} dt = \frac{V}{R_a \times T} \times \int_{P_1}^{P_2} \frac{1}{\left[\dot{w}_{in} - \left(0.5309 \times P \times A \times C \Big/ \sqrt{T_u}\right)\right]} dP \qquad \text{(Eq. 67)}$$

Integrating:

$$t' = \frac{V}{R_a \times T} \times \left(\frac{-\sqrt{T_u}}{0.5309 \times A \times C_D}\right) \times \left\{Ln\left[\dot{w}_{in} - \left(0.5309 \times P_2 \times A \times C_D \Big/ \sqrt{T_u}\right)\right]\right.$$

$$\left. - Ln\left[\dot{w}_{in} - \left(0.5309 \times P_1 \times A \times C_D \Big/ \sqrt{T_u}\right)\right]\right\} \quad , \text{ seconds} \qquad \text{(Eq. 68)}$$

or:

$$t' = \frac{V}{R_a \times T} \times \left(\frac{-\sqrt{T_u}}{0.5309 \times A \times C_D} \right) \times Ln \left[\frac{\dot{w}_{in} - \left(0.5309 \times P_2 \times A \times C_D \Big/ \sqrt{T_u} \right)}{\dot{w}_{in} - \left(0.5309 \times P_1 \times A \times C_D \Big/ \sqrt{T_u} \right)} \right] \quad , \text{ seconds} \qquad \text{(Eq. 69)}$$

After substituting the USCS choked flow Equation 22 from Section 5.2.1.3, Equation 69 simplifies to:

$$t' = -\frac{V \times P_1}{R_a \times T \times \dot{w}_{out1}} \times Ln \left(\frac{\dot{w}_{in} - \dot{w}_{out2}}{\dot{w}_{in} - \dot{w}_{out1}} \right) \quad , \text{ seconds} \qquad \text{(Eq. 70)}$$

Equation 70 is algebraically equivalent to AIR1168/7 Equation 3E-6 and can be used with both SI & USCS units.

An isothermal equation for the time for pressure change with both the initial and final pressures in the subcritical (un-choked) range can be derived in the same manner, if the relation for flow rate vs upstream pressure is simple enough to allow integration. Use of Fliegner's approximation for subcritical flow from SAE AIR1168/7 Section 4 does allow for a direct solution, if the flow coefficient is constant or can be represented by an average value. Data presented in Section 5.2.2 shows that the real behavior of orifices is complex and does not have a distinct choke point. The equations that define real orifice airflow do not lend themselves to derivation of simple depressurization rate equations. Dutton and Coverdill [1997] suggest that a solution using the subcritical ideal nozzle equations also is possible if the value for ratio of specific heats can be limited to a ratio of integers, such as 7/5 for room temperature air, but their solution is valid only for the case with no inflow.

SAE AIR1168/7 Section 4 provides the following relation for Fliegner's approximation for unchoked gravimetric flow rate (converted to the units of this report):

$$\dot{w} = 1.096 \times C_D \times A \times \sqrt{\frac{P_d \times (P_u - P_d)}{T_u}} \quad , \text{ lb/s} \qquad \text{(Eq. 71)}$$

$$\dot{w} = 0.08347 \times C_D \times A \times \sqrt{\frac{P_d \times (P_u - P_d)}{T_u}} \quad , \text{ kg/s} \qquad \text{(Eq. 72)}$$

As can be seen from FIGURE 6, Fliegner's approximation closely matches the flow rate calculated by the subcritical flow ideal nozzle equations from Section 5.2.1.4.

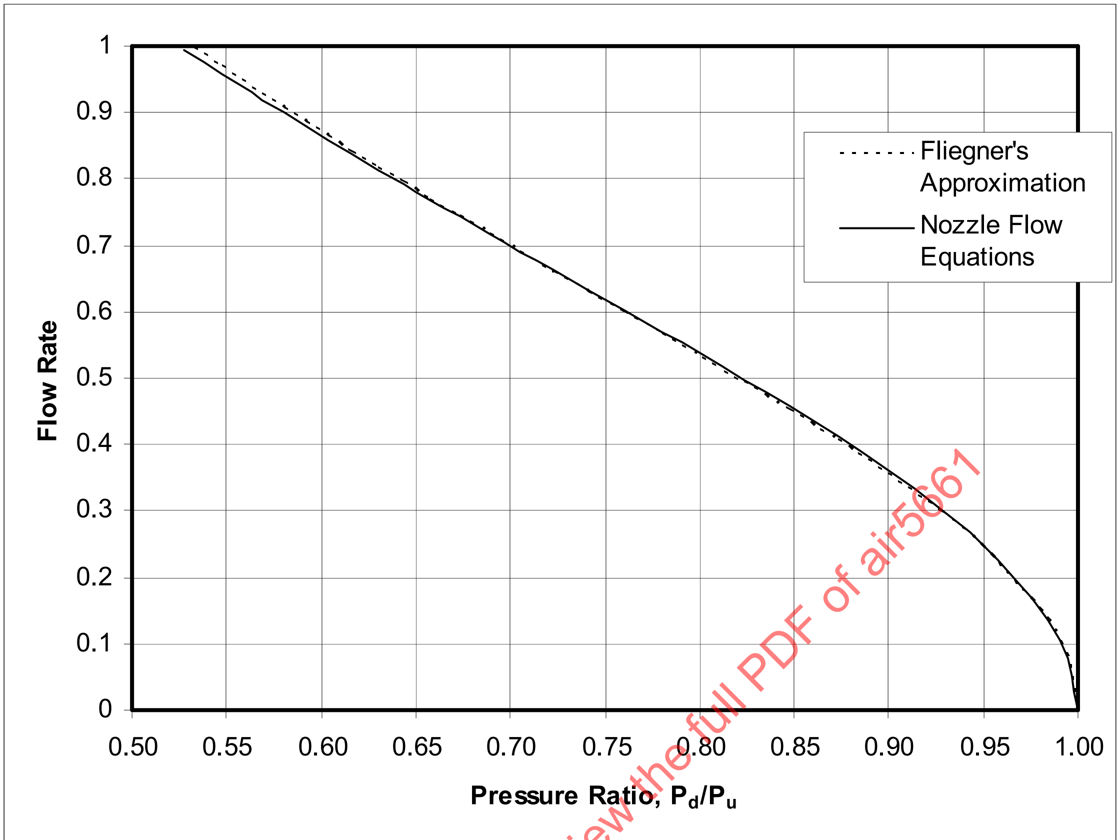

FIGURE 6- COMPARISON OF FLIEGNER'S APPROXIMATION TO IDEAL NOZZLE EQUATIONS FOR SUBCRITICAL FLOW

When Equation 71 is inserted into Equation 66 from Section 5.4.2 and integrated, the result is equivalent to AIR1168/7 Equation 3E-8:

$$t'' = \frac{2 \times V \times \left(\sqrt{P_{u1} - P_d} - \sqrt{P_{u2} - P_d}\right)}{b \times R \times C_D \times A \times \sqrt{P_d \times T_u}} + \frac{2 \times V \times \dot{w}_{in}}{P_d \times R \times \left(b \times C_D \times A\right)^2} \times \mathrm{Ln}\left(\frac{\dot{w}_{in} - \dot{w}_{out2}}{\dot{w}_{in} - \dot{w}_{out1}}\right) \text{, seconds} \qquad \text{(Eq. 73)}$$

Where:

b = 1.096 for USCS Units

= 0.08347 for SI Units

If the decompression is initially choked and passes through the critical pressure ratio, the total duration will be sum of the choked and unchoked durations.

5.4.3 Adiabatic Process

Very Rapid Decompressions cause significant air temperature drop, as evidenced by reports of condensation of moisture during in-service decompressions. Decompression chamber testing by Haber [1950] showed a temperature drop of almost 100°C (180°F) during the initial few seconds of a Very Rapid Decompression from SL to 15 240 m (50 000 ft) pressure altitude, but also that the temperature rapidly recovered due to heat transfer from the chamber walls.

An adiabatic process is one in which no heat is added or removed. It is governed by the following relation:

$$P_1 \times \nu_1^{\gamma} = P_2 \times \nu_2^{\gamma} \quad \text{(Eq. 74)}$$

where subscript 1 indicates the initial state and subscript 2 indicates the final state. From this equation and the ideal gas law, the relations between each of the air properties for an adiabatic process can be derived:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} \quad \text{(Eq. 75)}$$

$$\frac{T_2}{T_1} = \left(\frac{\nu_1}{\nu_2}\right)^{(\gamma-1)} \quad \text{(Eq. 76)}$$

$$\frac{T_2}{T_1} = \left(\frac{\delta_2}{\delta_1}\right)^{(\gamma-1)} \quad \text{(Eq. 77)}$$

Since compartment air density will depend only on the air mass and the compartment volume (which is constant), it follows that:

$$\frac{T_2}{T_1} = \left(\frac{w_2}{w_1}\right)^{(\gamma-1)} \quad \text{(Eq. 78)}$$

Combining Equation 78 with Equation 62 from Section 5.4.1 produces a relation that will predict the temperature (T_2) of the compartment air following an incremental adiabatic change in air mass.

$$\frac{T_2}{T_1} = \left(\frac{w_1 + dt \times \left(\dot{w}_{in} - \dot{w}_{out}\right)}{w_1}\right)^{(\gamma-1)} \quad \text{(Eq. 79)}$$

The compartment air pressure following the incremental change in air mass (P_2) can then be calculated from the ideal gas law. After simplifying, this relation is:

$$P_2 = \frac{R_a \times T_1}{V}\left(\frac{w_1 + dt \times \left(\dot{w}_{in} - \dot{w}_{out}\right)}{w_1}\right)^{\gamma} \quad \text{(Eq. 80)}$$

Equation 66 from Section 5.4.2 can be used to define the relation for the time required for an adiabatic expansion, except temperature will now also be a function of pressure.

$$\int_0^{t''} dt = \frac{V}{R_a} \times \int_{P_1}^{P_2} \frac{1}{\left(\dot{w}_{in} - \dot{w}_{out}\right) \times T} dP \quad \text{(Eq. 81)}$$

A direct solution to this equation is possible if there is no inflow (ref Dutton and Coverdill (1997)), but direct solutions with inflow and variable flow coefficients may not be possible.

Analysis presented by Haber [1950] shows that the presence of water vapor in the compartment air has the effect of increasing the air temperature, but decreasing the pressure during a Very Rapid Decompression. The temperature difference is caused by the latent heat of condensation of the moisture while the pressure effect is caused by the reduction in the ratio of specific heats. For the example given of 20°C (68°F) dry bulb temperature and 15°C (59°F) dew point temperature, which is equivalent to 49% relative humidity at SL, the depression in pressure is a maximum of about 10%. For a typical airplane cabin environment of 2438 m (8000 ft) pressure altitude and 10% relative humidity, the dew point temperature will be significantly lower at –6.6°C (20°F) which would delay the onset and reduce the magnitude of the effects.

5.4.3.1 Non-Ideal (Real/Polytropic) Process

The thermodynamic process of rapidly expanding air in an aircraft compartment will not be purely isothermal or adiabatic. For an extremely fast expansion, the behavior will approach adiabatic, while for a slow expansion the behavior will approach isothermal. The principal relation for a polytropic process is:

$$P_1 \times \nu_1{}^k = P_2 \times \nu_2{}^k \quad \text{(Eq. 82)}$$

Where:

k = Polytropic Constant

The adiabatic relations of Section 5.4.3 can be used for analysis of a polytropic process by substitution of k for λ. The value of the polytropic constant will be between 1 for an isothermal process and the value of λ for an adiabatic process. Testing by Haber and Clamann [1953] of simulated Very Rapid Decompressions using large steel chambers showed a polytropic constant of 1.16.

The value of the polytropic exponent can be determined from test data by the following relation, derived from Equation 82:

$$k = \frac{Ln(P_1) - Ln(P_2)}{Ln(\nu_2) - Ln(\nu_1)} \quad \text{(Eq. 83)}$$

Analysis of test data may show the calculated polytropic constant varies during the decompression. If so, the variation of the constant or of the cabin air temperature with time or cabin differential pressure can be defined by curve-fit or as a series of linear changes.

5.4.4 Stepwise Analysis

Direct solution of the equations defining a cabin decompression is possible for only a limited number of simple scenarios. In addition to the complexity of the equations, there are numerous changes that occur during a decompression (operation of isolation and outflow valves, operation of emergency pressurization system, emergency descent at a rate that varies with altitude, etc…) that would require the decompression be analyzed as a sequence of connected events. While this is possible, it may be unwieldy if numerous iterations are required such as when matching an analysis to test data.

If the decompression is broken down into a series of infinitesimal intervals, the changes in orifice flow coefficients, ambient pressure, compartment temperature, etc… can be recalculated at each interval. If the calculation interval is kept sufficiently small, the differences between a stepwise analysis and an exact direct solution will be imperceptible. This method would be unwieldy for hand calculation, but easily performed by computer.

The calculation interval can be based on the accuracy with which key events need to be captured and acted upon. For example, if the cabin altitude is expected to climb at 3600 m (12 000 ft)/min and the 3048 m (10 000 ft) cabin altitude warning event needs to be captured to the nearest 0.3 m (1 foot):

$$3600 \times \frac{1}{60} \times \frac{1}{(0.3)} = 200 \quad \text{Calculations Per Second}$$

The rate of compartment pressure change can be estimated from the time constant for decompression of that compartment. For an estimate, assume the flow rate can be predicted by the choked flow equations of Section 5.2.1.3. Substituting the choked flow rate Equation 22 from Section 5.2.1.3 into the rate of pressure change Equation 57 from Section 5.4.1 results in an equation with only time and pressure as variables (USCS units are used in this example). The flow rate has a negative value, because it is a rate of outflow:

$$\frac{dP}{dt} = -\frac{0.5309 \times C_D \times A \times P_u}{\sqrt{T}} \times \frac{R_a \times T}{V} = -\frac{0.5309 \times C_D \times A \times P_u \times R_a \times \sqrt{T}}{V} \quad \text{(Eq. 84)}$$

The pressure-time relation will be of the form of a first order differential equation:

$$\frac{dP}{dt} + C_1 \times P = 0 \quad \text{(Eq. 85)}$$

with a solution of:

$$P = P_1 \times e^{-\left(\frac{0.5309 \times C_D \times A \times R_a \times \sqrt{T}}{V}\right) \times t} \quad , \quad \text{lbf/ft}^2 \quad \text{(Eq. 86)}$$

The inverse of the term in parentheses is the time constant (τ); the time required for the pressure to decay 63% from its initial value. A reasonable initial calculation interval (dt) would then be $\tau / 100$. For an analysis with multiple compartments, the calculation interval would be based on the compartment with the smallest time constant.

A way to determine if the calculation interval is small enough is to perform the analysis using increasingly smaller steps until there is no significant change in the results. For a stepwise analysis of a Rapid Decompression, 100 calculations per second of simulation time is a reasonable initial frequency, while 100 000 or more calculations per second might be required for a Very Rapid Decompression simulation.

5.5 Inflow System Models

The flow through individual components of a bleed air inflow system can be represented by simple models of pressure or flow regulators combined with nozzle or orifice elements. The flow provided by complete inflow systems can vary widely, because of the combinations of these simple elements, sequencing of high and low engine bleed sources depending on throttle position or anti-ice bleed usage, operation of bypass valves for temperature control, whether control is manual, or automatic by input of airplane or cabin altitude etc. The following sections will provide models for a few simple components that can be used for modeling of a complete system. Since emergency descents are typically performed at minimum or reduced engine power, pressure drop in the supply ducting can be significant and should be included in the inflow system model.

In general, a flow control device will consist of a fixed or variable area nozzle or orifice that can be modeled using the equations from Section 5.2.1 or Section 5.2.2 as applicable to the device with a fixed or variable pressure source. Flight test data or an accurate model of the engine bleed air pressure available at engine power settings used for emergency descent is necessary for analysis of rapid decompressions, because flow rate calculations depend on the pressure available. Use of steady-state idle power setting engine bleed air pressure data for the entire emergency descent will be conservative. On indication of excessive cabin altitude, the crew action will be to reduce engine power from cruise power to the setting for best descent rate, typically the flight-idle power setting. Since engines can not respond instantaneously to crew commands, the engines may still be transitioning from cruise power to idle (descent) power when the descent has begun.

5.5.1 Unregulated Inflow Source

An unregulated inflow source has been used for emergency pressurization on some small airplanes. The unregulated source bypasses all temperature and primary flow controls. An orifice or nozzle is provided in the bleed air line that is sized to provide adequate inflow to maintain pressurization with engines at descent power setting. The temperature may be moderated by a heat exchanger or recirculating ejector, but flow rate is controlled entirely by the engine power setting. The variation of engine bleed pressure and temperature vs altitude is necessary to complete this model.

5.5.2 Pressure Regulated Inflow Source

A pressure regulator upstream of a flow throttling device (nozzle, venturi or orifice) will maintain a constant air volumetric flow rate for a given absolute supply pressure. Air mass flow rate will vary with air temperature. Gauge pressure regulators maintain a constant pressure above their reference pressure. If the regulator is referenced to ambient, the absolute outlet pressure will vary with altitude. If the regulator is referenced to the cabin, the absolute outlet pressure will depend on the cabin pressure. FIGURE 7 illustrates the difference in flow variation with altitude for a gauge pressure regulator referenced to ambient vs cabin pressure. In this example, the cabin pressure control system maintains SL pressure up to an altitude of 7315 m (24 000 ft), then maintains a differential pressure of 62 KPa (9.0 lbf/in^2) above this altitude. Bleed air inflow rate with a cabin referenced pressure regulator will vary with the cabin pressure control schedule. A cabin reference allows for less variation of inflow with altitude. However, some of this benefit is lost during a cabin decompression, since bleed airflow will decrease with cabin pressure.

If the bleed air supply pressure falls below the pressure regulator setting, flow will vary with bleed pressure. The pressure regulated inflow source model should include logic to calculate flow from either the regulator setting or the bleed air pressure, whichever is lower.

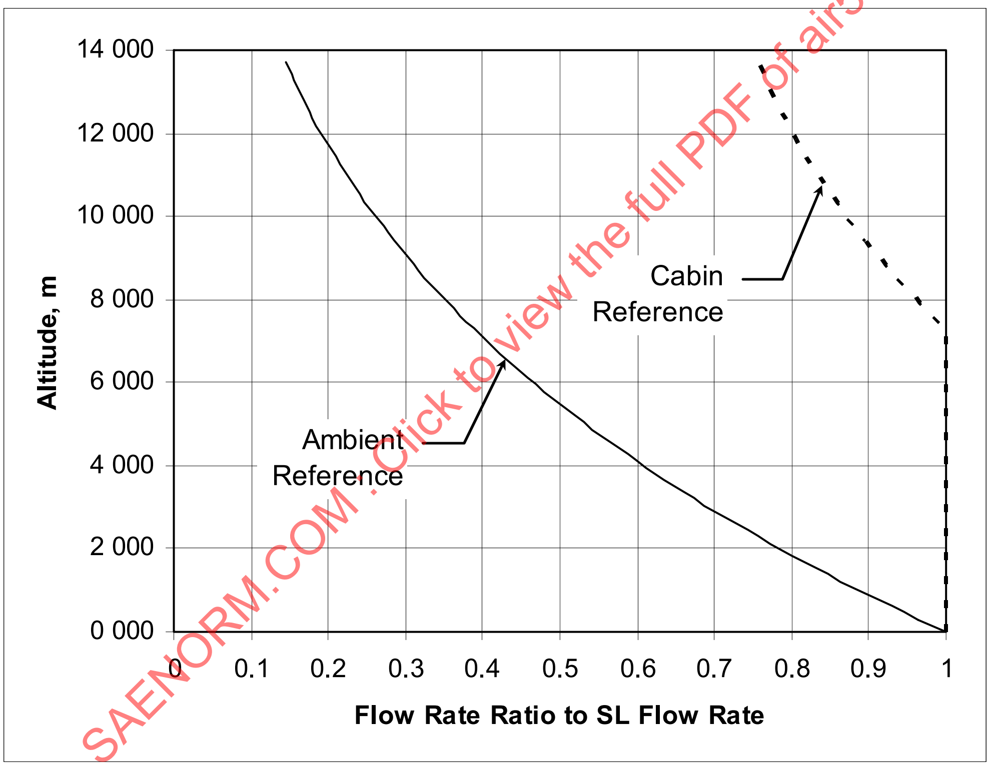

FIGURE 7- VARIATION OF BLEED AIR FLOW WITH ALTITUDE FOR CABIN AND AMBIENT REFERENCED PRESSURE REGULATORS

5.5.3 Flow Control Valves

Various flow control systems are in use that can schedule bleed flow according to altitude, heating and cooling loads, number of passengers, etc. The control rules for the flow control system should be modeled for accurate decompression analysis. It may also be adequate to model only the flow control mode that results in the lowest inflow rate that would be used following a rapid decompression, since that will be the critical case for analysis.

6. TYPICAL ANALYSIS SCENARIOS

The types of decompression analysis can be divided into the two categories of either rapid or very rapid. A Very Rapid Decompression will occur quickly enough that airplane altitude and ambient pressure can be assumed constant. It may also be possible to ignore the operation of outflow/safety valves, isolation valves and an emergency pressurization system if they can not act quickly enough to significantly affect the rate of decompression. If air passes through multiple partitions to the exhaust, the volumes of each compartment and flow characteristics of openings though each partition will need to be modeled. If venting of a compartment due to a Very Rapid Decompression relies on a relief panel with significant mass that requires buildup of a pressure differential to begin to move it, the inertia and flow characteristics of the panel will need to be accurately modeled.

Analysis of Rapid Decompression or Depressurizations, which can have durations of 5 minutes or more will require accurate modeling of atmospheric pressure during emergency descent and modeling of all components that affect air inflow or outflow rates. Unless an internal partition is specifically designed to impede airflow, such as a secondary pressure bulkhead equipped with isolation valves, it is generally acceptable to ignore internal partitions. If the pressure drops through internal partitions are ignored, this will result in a higher predicted rate of decompression, which is conservative for purposes of compliance with 14 CFR §25.841(a) and the corresponding high altitude Special Conditions.

Some analyses will have elements of both a Very Rapid and a Rapid Decompression. For example, if a secondary pressure bulkhead with a fast-acting isolation valve is provided to prevent decompression of the main cabin by a large leak in the secondary compartment, the large leak may cause decompression at a sudden rate until the isolation valve has closed. Depending on the design, the secondary bulkhead will then either prevent any further leakage or simply limit the rate of leakage to a rapid rate that can be mitigated by emergency descent. Results expected of analysis of this scenario will be both the prediction of cabin altitude for occupant effects and prediction of peak pressure loads across the secondary bulkhead.

For analysis of Rapid Decompressions, the highest cabin altitude will result when the highest initial cabin and airplane altitudes are used.

For analysis of Very Rapid Decompressions where the goal is to determine the peak pressure differentials across flow barriers, the highest peak pressure differentials will generally result from the condition that produces the highest initial cabin differential pressure and the highest absolute pressure in the discharging compartment. This condition occurs by setting the pressurized compartment pressure altitude to the lowest normal or approved pressure altitude and setting aircraft altitude to that which results in the maximum normal differential pressure. While this may not be a normal cabin pressure schedule, it is the critical condition for the decompression analysis and subsequent changes to the cabin pressure schedule will not affect decompression compliance.

For Very Rapid Decompression scenarios involving exhaust of air into a normally unpressurized compartment, the greatest pressure differential in the normally unpressurized compartment will generally occur starting with the pressurized compartment at its highest differential pressure and the normally unpressurized compartment at its lowest absolute pressure. This condition occurs at the maximum approved airplane operating altitude. Due to the large number of configurations possible for arrangement and volumes of internal and external compartments, analysis of Very Rapid Decompressions should be conducted at the maximum differential pressure but at both the maximum and minimum compartment absolute pressures.

Scheduling of some events will be variable and depend on the rate of decompression and crew actions. Numerous actions can occur during the 17 second crew action time.[18] Reduction of engine thrust by the crew in preparation for emergency descent may automatically command the inflow system to high stage bleed. Unless a particular sequence or timing can be defined from flight testing or AFM procedures, it is conservative to assume that all crew actions will not occur until the end of the crew action delay time.

Some events can have multiple triggers. Activation of emergency pressurization or high stage bleed can be made to occur automatically from detection of excessive cabin altitude or air conditioning pack shutdown, but may also be manually selectable by the crew as part of the emergency decent procedures. The model of this type of event should include logic to activate from either trigger, whichever occurs first.

[18] FAA AC25-20, Section 10.b.

Analysis methods have been provided for several simple decompression scenarios. More complex airplane configurations and decompression scenarios can be developed from these examples.

6.1 Rapid Decompression From Complete Loss of Inflow

This scenario assumes the following sequence of events:

a. All inflow air stops.

b. Cabin altitude rises.

c. The outflow control valves begin closing at their maximum rate.

d. At 3048 m (10 000 ft) cabin altitude (or whatever cabin altitude has been selected for warning of excessive cabin altitude), the crew action time delay (typically 17 seconds) starts.

e. At end of the crew action time delay, the airplane begins an emergency descent.

f. As the airplane descends, cabin pressure will approach ambient pressure. If the airplane is equipped with a ram fresh air ventilation system, the cabin pressure will be maintained at a differential equal to the aerodynamic dynamic pressure (q), minus inlet ducting losses. If no ram air pressurization is available, the cabin pressure will stabilize at the pressure setting of the negative differential valve plus outlet ducting losses.

The required input parameters for this analysis are at least the following. Additional inputs may be required depending on the complexity of the systems and models:

a. Effective cabin air volume

b. Normal cabin leakage area or the normal leak rate at a given cabin pressure and differential pressure

c. Outflow valve full open CA factor

d. Outflow valve full closed CA factor (Required only if outflow valve leakage is not included in the normal cabin leak rate)

e. Outflow valve closing time from full open

f. Cabin negative differential pressure relief setting

g. Initial airplane altitude

h. Initial cabin altitude or absolute or differential pressure

i. Cabin altitude warning (typically 3048 m (10 000 ft))

j. Crew recognition time (typically 17 seconds)

k. Airplane descent profile. Can be defined as a constant rate, a function or by tabular data of altitude vs time.

l. Mmo

m. Vmo

n. Ram air pressure available for cabin pressurization

o. Ram air inflow system effective CA

The last four parameters are required only if a ram fresh air source is provided. Dynamic pressure can be calculated from Mmo/Vmo per Section 5.1.3. If the characteristics of the ram air inlet and ducting system are well defined, the flow and pressure available can be calculated using AIR1168/1 or another suitable handbook. If the ram air system design is not defined, such as at the preliminary design stage, it can be omitted from the analysis. Ram air pressurization will have a relatively weak effect and will be present after the airplane has completely depressurized, which will tend to be at the very end of the emergency descent.

The initial cabin outflow area will be the normal cabin leakage area plus whatever open area is required for the outflow valves to maintain the given pressure differential with the normal inflow. After inflow has ceased and the outflow valves have closed, the cabin leakage area will simply be the normal cabin leakage area. The first steps of the analysis will be to define the initial states of the outflow valves and the air in the pressure vessel.

a. Given cabin pressure, air temperature and effective air volume, calculate mass of air in the compartment using Ideal Gas Law (Section 5.4.1). If cabin pressure altitude is defined instead of the absolute pressure, calculate the pressure from the standard atmosphere equations in Section 5.1.

b. Given the air inflow rate, calculate the total effective leakage area (CA factor) required at the given differential pressure using the nozzle flow equations from Section 5.2.1. Use of nozzle rather than orifice flow equations is justified for this purpose, because the upstream pressure and flow coefficient will not change significantly during the brief period required for the outflow valve to close.

c. Subtract the normal cabin leakage effective area from the total leakage area and calculate the time required for the outflow valve to move from this partially open area to fully closed per Section 5.2.4.2. Use of a different response characteristic model for the outflow valves may be necessary, if the response characteristics are highly non-linear, or if there is an initial delay in their response.

It can be conservatively assumed that loss of inflow will happen instantaneously. If loss of inflow due to closing of valves or loss of engine thrust occurs over a measurable period of time, the rate of inflow loss can be modeled. However, it should be noted that if the inflow has terminated before the cabin altitude has climbed through the 3048 m (10 000 ft) warning altitude, the rate of inflow loss prior to that point will have no effect on the peak cabin altitude, crew response or emergency descent profile.

Similarly, if the outflow valves can be assured closed before the cabin altitude has climbed through the 3048 m (10 000 ft) warning altitude, they can also be assumed initially closed and omitted from the analysis.

Once the initial conditions have been set and a calculation interval has been selected (refer to Section 5.4.4), the calculations can begin:

a. Calculate airflow rate from normal cabin leakage using the orifice flow equations from Section 5.2.2.2. Initially, flow direction will be outward. As pressure decays, if there is no ram air ventilation system, the airflow direction will turn inward during the descent once the negative differential pressure exceeds the negative differential pressure relief valve crackpoint. If there is a ram air system, the airflow direction will remain outward if the ram air system has the flow capacity to repressurize the cabin during the final part of the descent. Since the direction of airflow will depend on whether the cabin or ambient has the higher pressure and it can change during the descent, any automated calculation method will need to detect the correct direction and use the correct upstream and downstream pressures.

b. Calculate airflow rate through the outflow valves if they are open using the nozzle flow equations from Section 5.2.1 and the valve effective flow area from Section 5.2.4.

c. Calculate the dynamic pressure from Vmo/Mmo per equations in Section 5.1.3.

d. If installed, calculate ram air system inflow rate if cabin differential pressure is less than the dynamic pressure minus inlet and duct losses.

e. Add all of the rates of inflow and outflow, observing consistent sign convention (negative for outflow, positive for inflow).

f. Multiply the net outflow or inflow rate times the calculation time interval to determine the incremental change in compartment air mass.

g. Calculate the new cabin air mass.

h. Calculate the cabin air temperature. Selection of the appropriate calculation method should be justified by test data from previous similar aircraft designs.

   1. Isothermal- Unchanged from initial temperature.

   2. Adiabatic- Calculate from Equation 75 from Section 5.4.3 where the initial state (subscript 1) can be either the initial air mass and temperature, or the air mass and temperature from the previous interval.

   3. Real (polytropic)- Calculate from the relations in Section 5.4.3.1 if decompression test data is available from a previous similar aircraft design for calculation of the polytropic constant..

i. Calculate the new cabin air pressure using the Ideal Gas Law (Section 5.4.1).

j. Calculate the new cabin pressure altitude from the standard atmosphere equations in Section 5.1.

k. Increment the elapsed time.

l. If cabin altitude has passed the cabin altitude warning setting, begin counting the crew reaction time.

m. If the time since the cabin altitude passed through the warning altitude is greater than or equal to the crew reaction time, calculate the new airplane altitude from the descent profile (Refer to Section 5.1.4).

n. Calculate the new ambient pressure from the standard atmosphere equations in Section 5.1.

o. Calculate the new outflow valve effective flow area from Section 5.2.4. Zero if elapsed time is greater than the valve closing time from the initial partially open position.

p. Go to Step a.

The calculations can be terminated after a fixed time or when the airplane or cabin altitude reach a target value, such as 1524 m (5000 ft), as recommended by FAA AC 25-20, Section 10.d.

Outputs of the calculations will be:

a. Elapsed time

b. Airplane altitude

c. Cabin pressure altitude

d. Any other parameters, as may be necessary to ensure the correct input values have been used and the program has executed as expected.

6.2 Rapid Decompression From Pressure Vessel Rupture With No Loss of Inflow

The events of this scenario will be similar to those of Section 6.1. Several of the events will depend on the inflow system architecture and controls. This scenario assumes the following sequence of events:

a. Sudden increase in cabin leakage area.

b. Cabin altitude rises.