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AEROSPACE RECOMMENDED PRACTICE

ARP 1270

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Revised

AIRCRAFT CABIN PRESSURIZATION CONTROL CRITERIA

1. PURPOSE

1.1 The purpose of this recommended practice is to provide the aerospace industry with guidelines as to the pertinent technology relating to the physiological considerations, the technical system requirements and design objectives for aircraft pressurization control systems.

1.2 This recommended practice is applicable to pressurized aircraft regardless of the number of passengers or crew. The pressurization control system must provide maximum safety and passenger and crew comfort as a result of changes in cabin pressure altitude during the entire aircraft flight and during ground operation.

2. SCOPE

2.1 These recommendations cover the basic criteria for the design of aircraft cabin pressurization control systems as follows:

(1) To ensure aircraft safety.

(2) Physiology and limits which govern maximum permissible pressure time relations as related to aircraft passenger comfort.

(3) General pressurization control system performance requirements designed to satisfy (2).

(4) Technical considerations relevant to satisfying (3).

3. PHYSIOLOGY OF CABIN PRESSURE CHANGES

3.1 Types of Cabin Pressure Changes

3.1.1 The physiological effects of cabin pressure changes are inevitably the ultimate criteria by which the airline passenger and crew evaluate cabin pressurization control system performance. The source of these effects fall into two broad categories: (1) pressure transients (bumps) and (2) slower pressure changes.

3.1.2 Pressure bumps are short duration cabin pressure changes of sufficient magnitude to cause passenger discomfort. Proper design of the controls and equipment of the air conditioning and pressurization systems can minimize bumps and significantly enhance passenger comfort.

3.1.3 Unless an aircraft flies pressurized at the pressure altitude of the take-off port to a port of destination of equal altitude, a change in cabin pressure must take place during the flight. If an aircraft need only change its cabin pressure continuously from that at take off to that at the landing field, the control problem would be simple. However, this method is possible on only a limited number of flights, since during most flights the aircraft cabin altitude must be increased as the aircraft climbs to cruise altitude so as not to exceed the aircraft design cabin pressure-to-aircraft ambient pressure differential. Generally, aircraft designed for airline service are capable of maintaining a cabin altitude of 6000 to 8000 ft (1.83 to 2.44 km)* when the aircraft is at maximum cruise altitude. Design for a sea level pressure in the cabin while the aircraft is at maximum altitude presents a structural weight

*Number in parentheses represent International (SI) Units. Refer to the section titled "SI Conversions and Abbreviations".

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penalty. Therefore, for practical considerations the pressure within the aircraft cabin must be varied during the flight; this variation must be controlled by the pressurization control system to minimize passenger discomfort.

3.2 Ear Physiology

3.2.1 Discomfort from changes of ambient pressure results foremost from its effect on the middle ear. From the standpoint of pressurization control systems, the ear may be considered as an air-filled, closed cavity with pressure equalization possible only when the eustachian tube is open (Figure 1). We can support this statement best by a review of the anatomy of the ear.

3.2.2 Three basic sections of the ear are the outer, middle and inner ear.

The outer ear consists of the external fleshy ear and the external auditory canal terminating at the eardrum (tympanic membrane).

On the other side of the eardrum is the cavity of the middle ear. Near ambient pressure is maintained in the middle ear cavity through the internal auditory canal, the eustachian tube. Sound waves are sensed as a momentary pressure differential across the eardrum which causes the eardrum to oscillate. Movement of the eardrum is magnified by the leverage of the ossicles (the ear bones) and is directed to the inner ear.

The inner ear consists of the cochlea, which is shaped like a snail, and the semicircular canal. The fluid-filled cochlea reacts to movements of the ear bones and transmits nerve impulses to the brain. When a constant pressure differential exists across the eardrum, the ear bones are displaced and the pressure detected by the inner ear causes an uncomfortable feeling.

3.2.3 Near the middle ear cavity, the eustachian tube is surrounded by bone and remains open. Near the nasal passage, the eustachian tube is normally closed by the surrounding membraneous tissue.

The eustachian tube opens occasionally by involuntary contraction of the eustachian tube dilator muscles, called salpingopharyngeal muscles. The action equalizes pressure across the eardrum. Voluntary opening of the eustachian tube can be accomplished by swallowing, yawning or by learned contraction of the dilator muscles. This learned contraction can be accomplished, with practice, by suppressing a simulated yawn, at which time a roaring in the ears will indicate when the effort is successful.

3.2.4 Positive pressure in the middle ear tends to force the eustachian tube open and is self-relieving.

3.2.5 Negative pressure in the middle ear tends to hold the eustachian tube closed. For this reason, ear discomfort caused by pressure changes are associated with descent in cabin pressure altitude.

3.3 Physiological Effects

3.3.1 Figure 2 illustrates the physiological effects of pressure differential.

3.3.2 Excess differential pressure across the tympanic membrane will cause it to rupture. Rupture of the membrane itself is preceded by rupture of the blood vessels crossing the membrane, thus causing bleeding from the middle ear. Hearing ability of the affected ear is degraded about 30 db until healing restores the ear to its original capability.

Healing is evident within 12-24 hours and is usually complete within two weeks to a month.

3.4 Cabin Pressure Bumps

3.4.1 The pressure bump required to reach the threshold of feeling varies for different individuals. Also the threshold of feeling for any particular individual is dependent upon the rate of

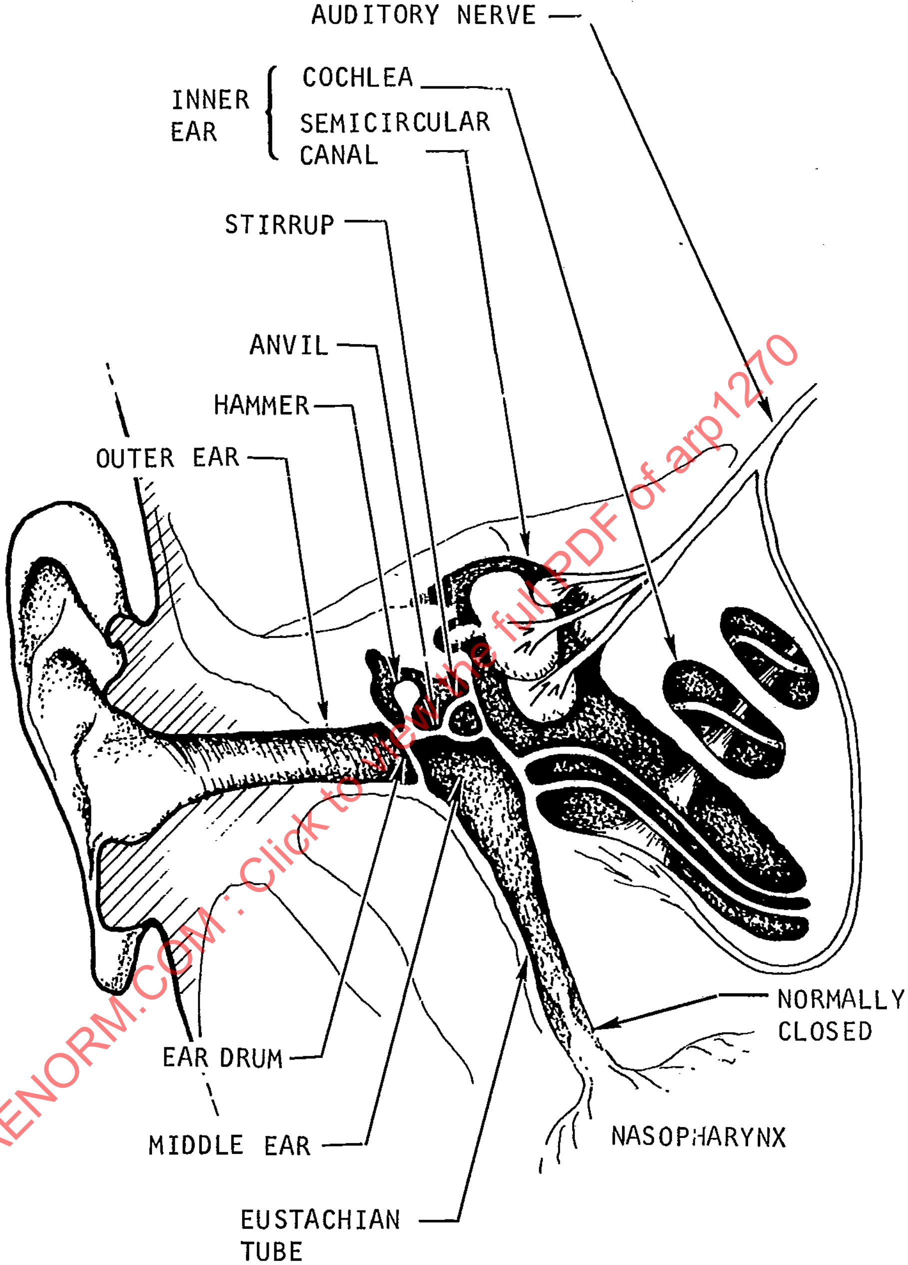
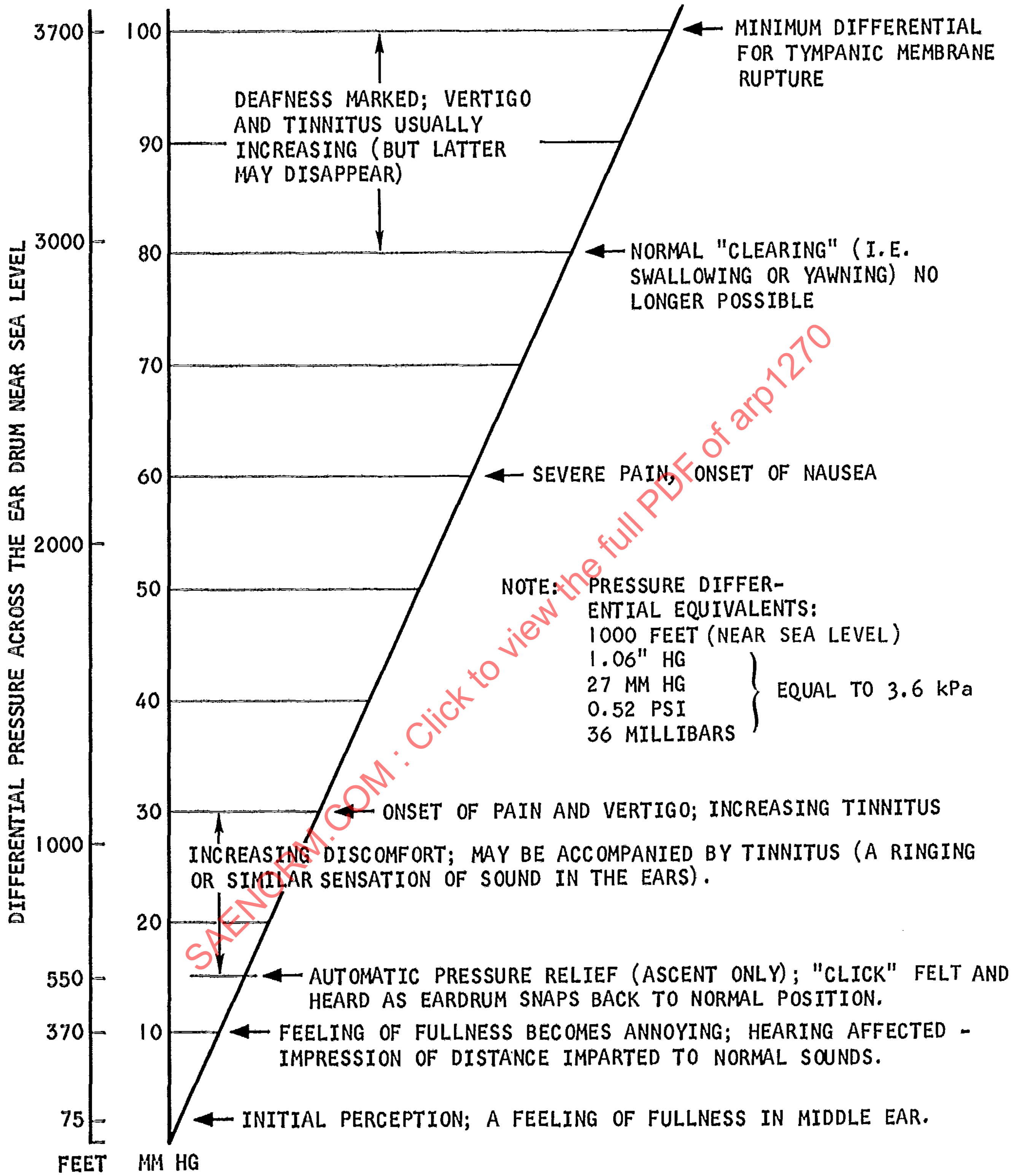


Figure 1. Physiology of the Human Ear



Note: Refer to the section titled "SI Conversions and Abbreviations" for conversion factors to SI units

Figure 2. Physiological Effects of Pressure Differential on the Normal Human Ear (Increasing Pressure Only)

change of pressure. The ear is less sensitive at the rates of change normally associated with scheduled [300-500 fpm (91 m/60s to 152 m/60s)] cabin pressure changes (see Figure 3). The results of the work of several investigators show no threshold of feeling lower than 60 feet* (18 m) altitude change.

3.4.2 One method of defining design limits for cabin pressure bumps, based on threshold of detection by humans is shown in Figure 4.

3.4.3 Another method known as the Equivalent Eardrum Differential Pressure (EEDP) method considers the sensory perception of the average individual on the basis of time integration of the eardrum differential pressure due to rate changes. This method (see Reference 7) is based on a fixed physical model of the human ear and gives results similar to those shown in Figure 4.

3.5 <u>Sustained Pressure Increase</u>

3.5.1 The human ear is capable of withstanding extremely rapid pressure increases. Tests have demonstrated these capabilities at rates far in excess of commercial airline requirements. However, the subjects of these tests were healthy adults with normal ears. They were well trained in the techniques of clearing the middle ear during rapid descent.
Repeated descents from 9500 feet (2.89 km) to sea level pressure in 5 seconds [45 mm Hg/sec (6 kPa/s)] were recorded without sinus pain or discomfort.

3.5.2 Commercial airline travel is measured in the tens of millions of passengers annually. This group includes large numbers of individuals who are unable to ventilate the middle ear properly during descent. These are sleeping passengers (swallowing at increased intervals); children; passengers with colds, sinus congestion, or abnormal ear passages; and passengers who are ignorant of the techniques of equalization of pressure in the middle ear. The average person swallows involuntarily about every sixty to seventy-five seconds. A rate of climb or descent of 200 fpm (61 m/60s) will usually cause no discomfort; 500 fpm (152 m/60s) ascent or 300 fpm (91 m/60s) descent will cause only slight discomfort even though no effort is made to ventilate the middle ear artifically.

*Based on sea level pressure

4. CABIN PRESSURIZATION CONTROL SYSTEM PERFORMANCE REQUIREMENTS

4.1 The requirements for a pressurization control system are many and complex. Certain requirements are basic and are not subject to debate. Foremost is the need to insure the safety of the aircraft during normal and abnormal flight and to provide for pressurization system component malfunctions.

4.2 The above requirements apply during all reasonably probable failure conditions, but another, less tangible, set of requirements apply during normal operation. The latter are dictated to provide a high level of passenger comfort.

4.3 Beyond these requirements of safety and comfort there are other factors to be considered. These include crew size and workload, degree of automation (or sophistication), cost, and weight.

4.4 In addition to provisions to control the maximum cabin-to-ambient positive ΔP limit and the cabin-to-ambient negative ΔP, the system should include means to select the cabin altitube and control the rate-of-change of cabin pressure. In the past, aircraft and cabin pressurization system designers have used as design limits for passenger comfort 500 fpm* (152 m/60s) cabin climb rate and 300* fpm (91 m/60s) cabin descent rate. Recent airline surveys have indicated that these are acceptable limits based on actual airline operator experience. Should normal operation of an aircraft require cabin rates exceeding these limits, some loss in passenger comfort should be expected.

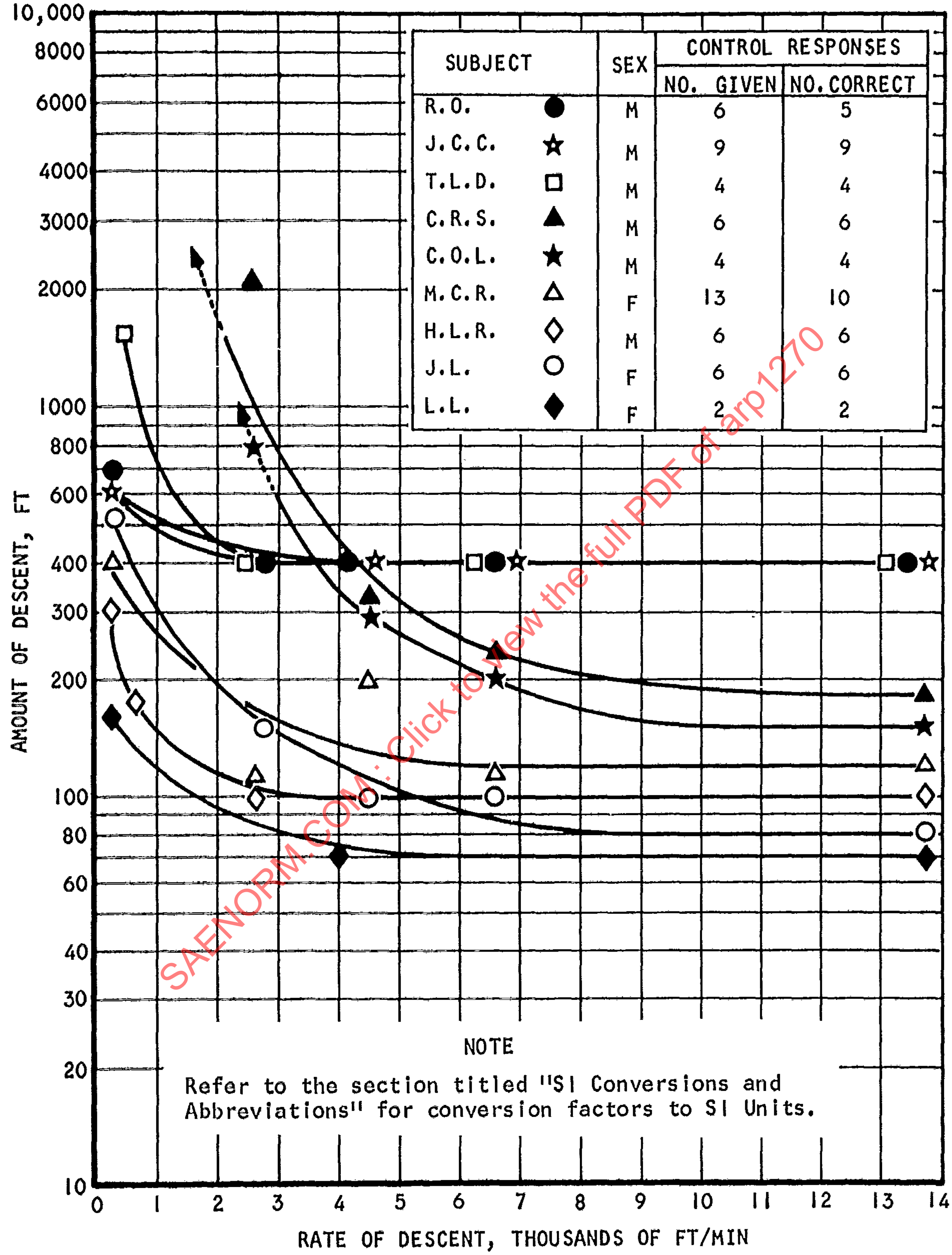


Figure 3 Altitude Changes Just Perceptible to the Middle Ear in Relation to Rate of Descent. (Reproduced from "Middle Ear Perception," Spealman and Cherry, Aviation Medicine," February, 1958)

NOTE: Refer to the section titled "SI Conversions and Abbreviations" for conversion factors to SI Units.

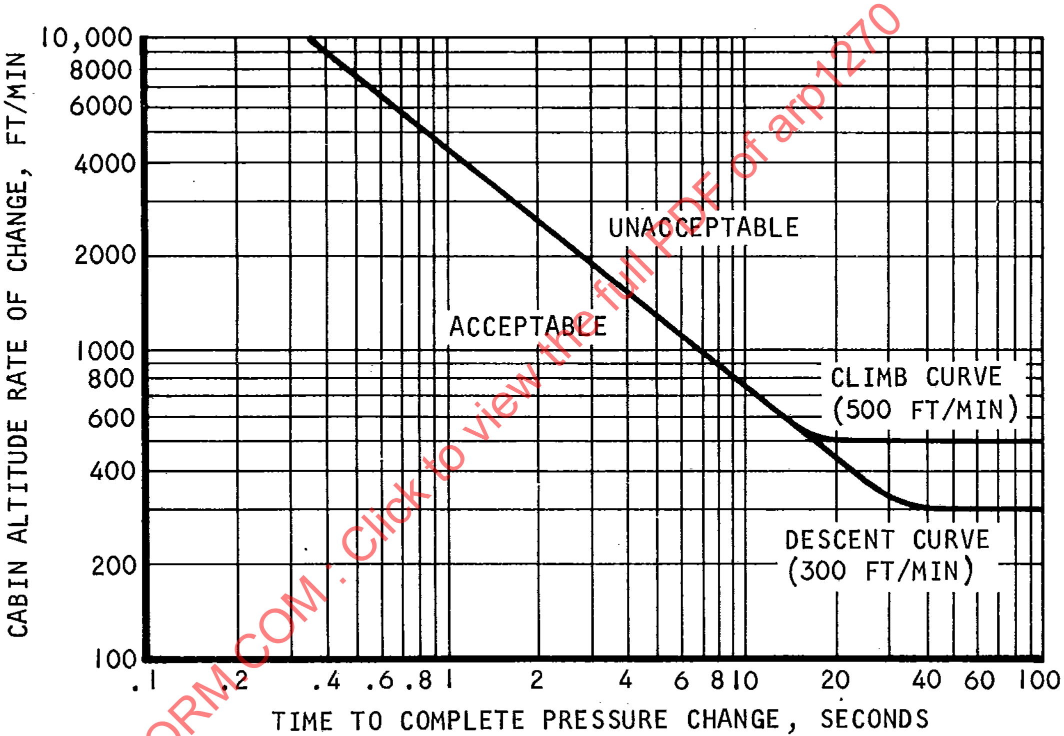


Figure 4. Design Limits for Short Duration Cabin Pressure Changes, Based on Threshold of Detection by Humans

4.4.1 This type of system (selectable isobaric) allows the crew to select the cabin altitude and the rate-of-change of the cabin altitude. During climb, the pressurization control system should control the rate of climb of cabin altitude at the value selected by the crew. During cruise, the system should control the cabin pressure to within 125 ft (38 m) of the selected value. Experience has shown that this performance is adequate for many commercial aircraft and that increased limits [up to 200 ft (61 m)] may be satisfactory for military, small or intermediate size aircraft depending upon weight, cost, complexity and logistic considerations. The range of isobaric cabin control should be adjustable from -1000 ft (-304.8 m) to 10,000 ft (3 km). Aircraft certified for operation using airports above 10,000 ft (3 km) should include provisions for increasing the adjustable range to -1000 ft (-308.4 m) to 14,000 ft (4.3 km). The cabin rate of change should be smoothly adjustable from a minimum rate of as low as 50 fpm (15 m/60s) to not less than 750 fpm (229 m/60s). Means of limiting the cabin altitude to less than 15,000 ft (4.6 km) during failure of the control system must be provided as part of the system. During descent, the landing field elevation may be selected along with the appropriate cabin descent rate so that the cabin pressure will arrive at the correct landing field barometric pressure prior to landing.

4.4.2 In order to reduce crew work load, some fully automatic systems monitor the aircraft performance and respond automatically when the aircraft altitude is changed. This allows the crew to preselect (prior to take-off) the expected landing field elevation and requires no further crew action other than to correct the system for the landing field barometric pressure during descent.

4.4.3 Passenger comfort requires that the system have adequate response to handle the transients that result from take-off rotation, engine power change, adding or subtracting a cooling pack and engine bleed stage switchover operation. The system may be required to operate so as to maintain a prepressurized cabin on the ground [in the range of 50 to 300 ft (15 m to 91 m) below field elevation]. However, this must be consistent with regulations governing door opening requirements.

To provide an acceptable level of passenger comfort the system should include means to limit cabin pressure bumps to a short duration change in cabin pressure altitude not to exceed 60 to 80 ft (18 m to 24 m). These short duration pressure changes are caused by one or a combination of the following:

(1) High rates of change of cabin air inflow which may be caused by rapid engine or cabin air source variation.
(2) High rates of change of local ambient static pressure at the overboard location of the cabin air outflow valve, such as may occur during aircraft rotation just prior to takeoff.
(3) Lack of responsiveness of the cabin pressure control system.

The cabin pressure control system should be designed to provide adequate control with the maximum cabin air inflow rate change either increasing or decreasing. Depending upon the cabin air source, a cabin inflow rate control may be desirable.

The cabin pressure system should also be designed to function with the maximum rate of change of local ambient pressure at the outflow valve exhaust port. If, due to the location of the outflow valve, the local ambient pressure exceeds the desired cabin pressure, aerodynamic means should be added to reduce the local ambient static pressure to an acceptable value.

The pressurization control system response should be consistent with the design limits shown on Figure 4.

4.5 Provisions to manually intervene and override the automatic system must be incorporated. This should be accomplished with the minimum number of crew actions possible.

4.5.1 For fully automatic systems, the control system must monitor the significant performance parameters and, during certain types of failure, take the appropriate corrective action.

4.5.2 The increments of cabin pressure rate of change for systems which exhibit step change characteristics should be less than 300 fpm (91 m/60s) under manual control.

4.5.3 The manual system should be capable of cabin rate of pressure change of not less than 2,000 fpm (609.6 m/60s).

4.6 The flight crew should be provided with means to monitor the following:

(1) Cabin pressure rate of change
(2) Cabin pressure altitude
(3) Cabin pressure-to-ambient differential
(4) Outflow valve position (for commercial transport aircraft)

4.7 An audible warning signal should be provided to indicate when altitude of the commercial aircraft cabin has become excessive [not to exceed 15,000 ft* (4.6 km)].

4.8 Manual systems and automatic systems on manual control must include features that provide for aircraft structural protection at all times.
If the aircraft is to be certified for over-water flights, the outflow valves and vacuum relief valves should be installed such that water does not enter the fuselage during ditching. If this cannot be accomplished, provisions must be included to close the valves prior to ditching. Closure of the valves should be automatic but consistent with other design considerations.

5. CABIN PRESSURIZATION CONTROL SYSTEM TECHNICAL DESIGN CONSIDERATIONS

5.1 The aircraft cabin pressurization control system design must consider the following criteria listed in order of precedence:

(1) Safety
(2) Passenger Comfort
(3) Economic factors, crew convenience

5.2 The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that:

(1) Catastrophic failure is extremely improbable.
(2) Failures which would have a major effect on the operation of the airplane (major failures) are minimized, and the airplane can be flown and landed safely after such a failure, without serious hazards to the occupants, and without requiring exceptional skill or strength on the part of the crew. A major failure may involve a single failure or a combination of failures.
(3) Failures other than those described in (1) and (2) will have only minor effects on the airplane or occupants (minor failures), and can be readily counteracted by the crew.
(4) For commercial airline aircraft provisions should be made to isolate system malfunctions to line-replaceable components without the necessity of pressurizing the airplane.

*Warning at 10,000 ft (3 km) is suggested to provide time for the flight crew to correct, if possible, the pressurization malfunction, to minimize passenger discomfort, and also to possibly prevent oxygen mask drop. In addition to the audible warning, a visual warning signal should be incorporated whenever possible.

5.3 The cabin pressure control system must operate to provide desired comfort levels during at least the following segments of the flight.

(1) Door closure and air inflow initiation
(2) Taxi from ramp
(3) Take-off and transition from "ground" to "flight" mode
(4) Climb
(5) Cruise (or holding)
(6) Descent and barometric correction
(7) Landing and transition from "flight" to "ground" mode
(8) Taxi to ramp
(9) Door opening

5.4 General recommendations for cabin pressure regulating equipment are covered in ARP 367, Sections 3 and 5. Control and sensing lines and ports shall be located, sized, and routed in accordance with ARP 367, Paragraph 5.4. (Certification requirements for small and transport aircraft are contained in the FAR regulations listed in references (9) and (10).

5.5 Qualification test requirements for cabin pressurization control equipment should be specified based on the applicable tests covered in MIL-STD-810.

5.6 If aircraft electrical power is used by the system or components, consideration must be given to power interruptions (for up to five minutes for commercial airliners). The system must be designed to tolerate this power loss without danger to the aircraft or occupants. The system and compoents must also be designed to provide normal or required performance during normal expected electrical power source variations.

5.7 Cabin Pressurization Control System Components - The simplest cabin pressure system includes at least an outflow valve set to control the cabin pressure to a constant cabin-to-ambient ΔP and safety valves used to prevent aircraft structural damage should the outflow valve fail.

5.7.1 <u>Outflow Valve</u> - All cabin pressure systems incorporate a valve or valves which regulate the cabin overboard flow rate (the cabin inflow air rate minus leakage) so as to control the pressure inside the cabin.

The outflow valve shall be so designed and matched with airframe design as to permit complete pressure control at full design differential with one air inflow source inoperative.

Outflow valve design shall minimize both the accumulation of tars, dirt, etc., and the effect of any such accumulations on operation.

Systems that have two or more outflow valves should be able to permit complete pressure control over the full pressurization design range with all inflow sources operable and one outflow valve inoperative. This capability enhances aircraft dispatchability.

Outflow valve location has an effect on the airflow distribution within the airplane cabin. Location of the outflow valve(s) at one end of the cabin can cause maldistribution of the cabin airflow, with higher than desired air velocities (drafts) at the end of the airplane near the valves, and less than required airflow at the extreme opposite end. Air collection ducting, and use of the under-floor area as a collection center have been useful in combatting this effect.

Outflow valve acoustic noise levels shall be considered in the location of the valves within the cabin. Acoustic treatment of the valves may be required due to the high velocities of the air exiting through the valve under high flow operating conditions, especially in small cabin aircraft wherein the outflow valve is near the airplane occupants.

The outflow valve exit characteristics are highly affected by the slip-stream effects. Gross changes in the slip-stream characteristics may cause pressure bumps. The phenomenon is especially critical at rotation, during the airplane takeoff roll. The location of the outflow valve with regard to unstable, or inconsistent slip-stream effects should be considered. Wakes from variable surfaces (control elements, landing gears and thrust reversers) should be avoided. Spoiler devices may be utilized during flight regimes where inconstant slip-stream conditions cannot otherwise be avoided by proper location of the valves.

5.7.2 Relief Valve - Special purpose valves must be included to prevent damage to the aircraft structure due to excessive pressure differentials.

5.7.2.1 For large transport aircraft, two cabin positive pressure relief valves, commonly called safety valves, shall be provided. These valves are normally closed.

Safety valves shall be independent of each other and sensing plumbing shall be independent of all other sensing systems.

The safety valve shall be sized to permit control of pressure for any burst pneumatic duct which may occur within the pressurized volume.

Sensing ports shall be located to give accurate, consistent indication regardless of airplane altitude or speed. Safety valves shall be designed to regulate at relief setting and shall not "dump" the cabin.

System design shall incorporate a margin between the upper tolerance limit of maximum normal differential pressure control and the lower tolerance limit of the relief valve to prevent control overlap.

5.7.2.2 Negative relief shall be provided to protect the airplane from excessive negative pressure. This feature is sometimes included in the safety valve. Two negative relief valves are required unless the design is simple enough to reasonably preclude malfunction. A swing check device is considered adequate to meet the single valve requirement.

5.7.3 Altitude Selector - Aircraft cabin pressure control systems can be categorized as either fixed or variable isobaric systems. These terms relate to the basic purpose of cabin pressure control, which is to regulate cabin pressure to a constant altitude at a comfortable level independent of aircraft flight altitude. Fixed isobaric systems do not incorporate a means of selection of the isobaric altitude. These systems always limit cabin altitude at the same level and the cabin is allowed to climb with the aircraft up to this level. Fixed isobaric systems are generally used on military aircraft where freedom from crew attention is imperative and comfort is a secondary consideration.

Variable isobaric systems incorporate an altitude selector permitting the crew to vary the selected isobaric cabin altitude based on the flight plan and aircraft structural safety pressure differential limitations. The selector is mounted in a location accessible to the crew. The face panel of the selector is provided with control knobs and indicator scales for adjustment of the isobaric altitude. Typically, depending on the type and sophistication of the control system, a knob and scale is provided for limitation of cabin pressure rate of change, and for making correction for variation of the landing field barometric pressure, for outflow valve position indication and balancing control, for switching between system operating modes, for safety warning lights, etc. The altitude selector is the instrument whereby crew inputs are relayed to the cabin pressure control system.

5.7.4 Cabin Pressure Controller - The unit which receives the input signals from the altitude selector and provides an output signal for control of the outflow valves is commonly called the cabin pressure controller. For pneumatic systems the altitude selector and controller functions are often incorporated in a single unit mounted in the crew compartment. For this type of controller the input selections provide mechanical adjustments to the pneumatic controls and the output signal is in the form of pressure. For systems using electronic controllers, the controller is usually located remote from the altitude selector and the input and output signals are electrical.

5.8 Types of Cabin Pressure Control Systems

5.8.1 Pneumatic - Figure 5 shows a typical fixed isobaric type pneumatic system. All control functions and outflow valve actuation are accomplished with pneumatic pressures. Manual override devices in this type of system (for instance, for dumping the cabin) can be either mechanical or electrical solenoid operated.

Figure 6 shows a typical variable isobaric type pneumatic system with the selector and controller functions combined in a single component. Electrical energy is commonly used in this type of system only for lighting the panel of the controller unit and operation of solenoid valves for automatic and manual switching of operational modes.

5.8.2 Electronic - Figure 7 shows a typical electronic cabin pressure control system. All control functions except pressure sensing make use of electrical power. Outflow valve actuation is performed electrically. The cabin pressure controller is an electronic modularized unit incorporating pressure sensing, logic and signal generating circuitry.

5.8.3 Pneumatic/Electric hybrid systems which employ both electrical and pneumatic control elements are in use. The designation, pneumatic/electric, is assigned to those systems which utilize a pneumatic controller for sensing and generation of a pneumatic pressure command, a transducer element for conversion of the pneumatic signal to an electrical signal, and electrical elements for control and actuation of the outflow valves.

5.8.4 Electro/Pneumatic - This designation is assigned to the hybrid systems which use pneumatically operated, electrically controlled, outflow valves. A typical system of this type is shown in Figure 8.

5.9 Automatic Cabin Pressurization Control Systems

The automaticity of a cabin pressure control system is entirely relative. All systems contain many automatic functions. The simple fixed isobaric pneumatic system shown in Figure 5, for instance, is completely automatic. That is, provision is made for manual override only for an emergency condition. In general, as the degree of desired cabin pressure comfort increases, the system complexity increases, and typical commercial airliner systems incorporate a considerable number of automatic features eliminating the necessity for crew attention. Automatic electronic systems are often defined as systems containing logic elements which automatically adapt the mode of cabin pressure control to changes in flight plan after takeoff. The most modern of automatic systems permit the crew to select the landing field elevation prior to takeoff and to use any desired flight profile without inflight adjustment of the system.

5.10 Valve Sizing

5.10.1 Outflow Valve Sized for Unpressurized Operation

The method outlined below may be used to determine the total system CA (effective flow area) requirement for unpressurized operation. In sizing for unpressurized operation, consideration must be given as to whether any other valves will be used to augment the outflow valve capacity. Small aircraft are designed for a cabin-to-atmosphere differential pressure of 0.5 in. Hg (1.7 kPa) or less for ground operation with full air inflow rate to the cabin. Large aircraft are designed for the minimum practical cabin-to-atmosphere ground differential pressure during ground operation--usually a few inches of water (approximately 750 Pa) with full air inflow. The following formula is a simplification of the relationship for compressible fluid flow and is accurate enough to determine the CA requirement provided the ΔP does not exceed 10 percent of P_i. This condition will always be met with the cabin pressure near sea level.

$$W = 8.76\ CA\sqrt{\frac{P_i\ \Delta P}{T_i}}$$

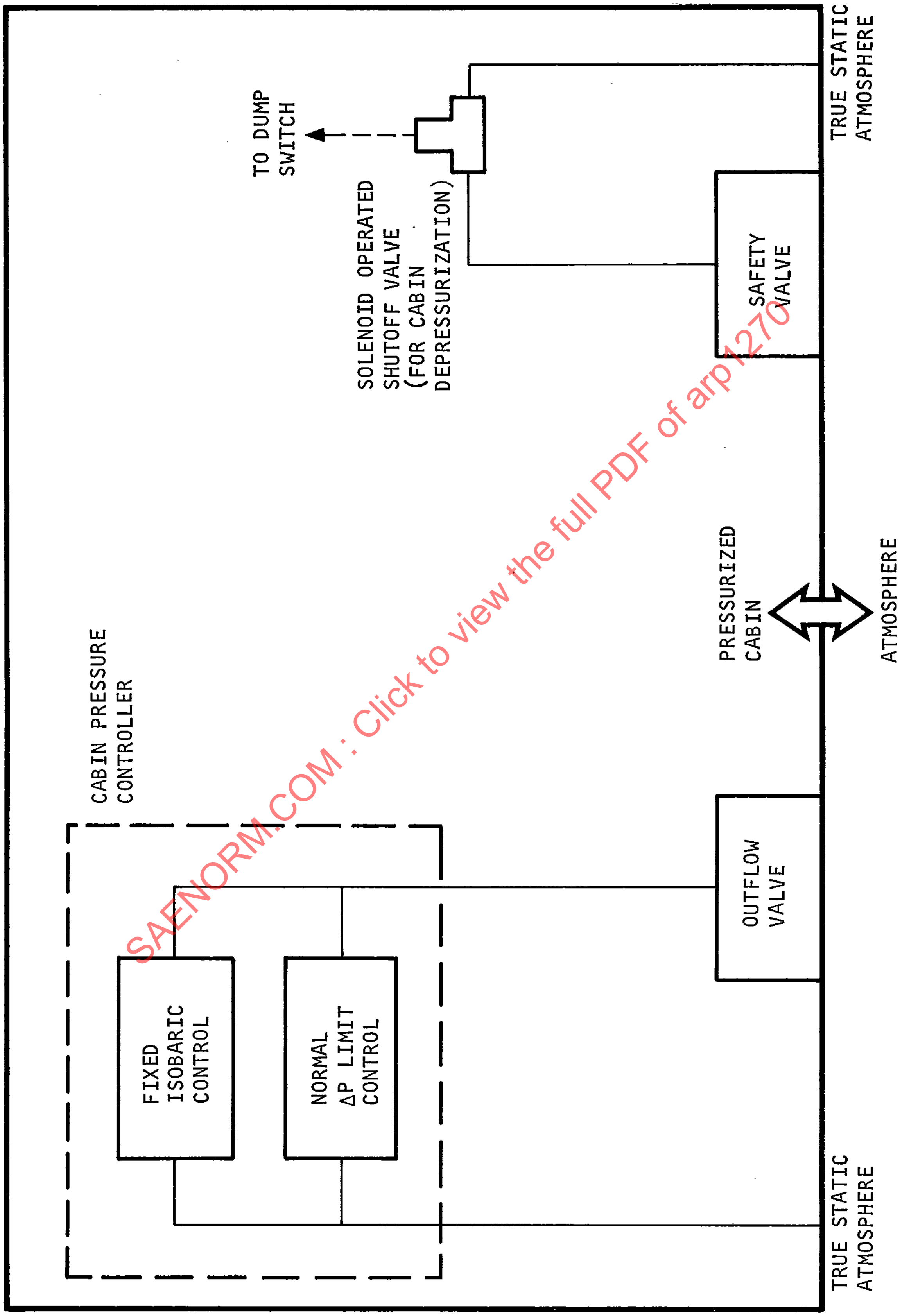


Figure 5. Fixed Isobaric Pneumatic Pressure Control System

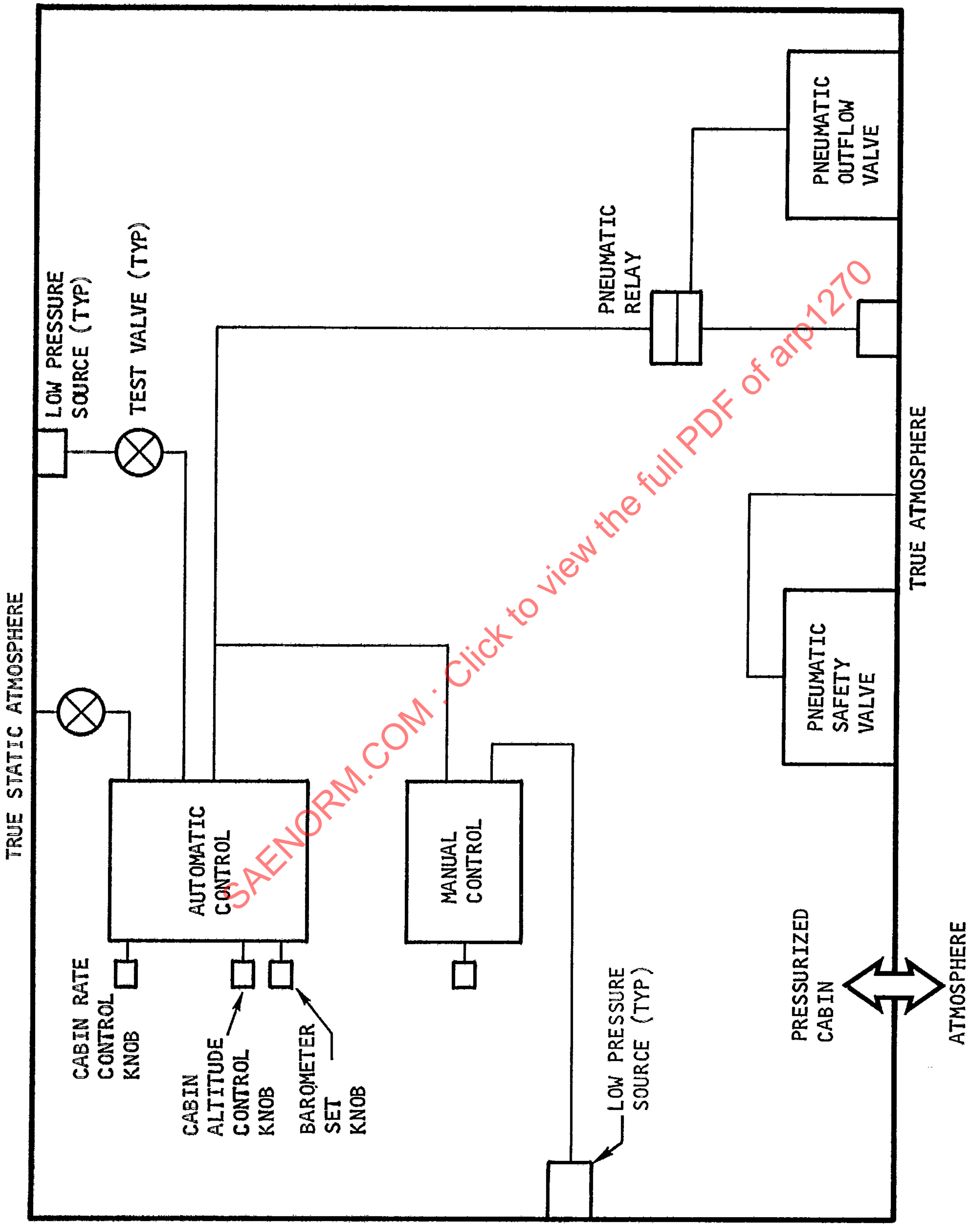


Figure 6. Variable Pneumatic Cabin Pressure Control System

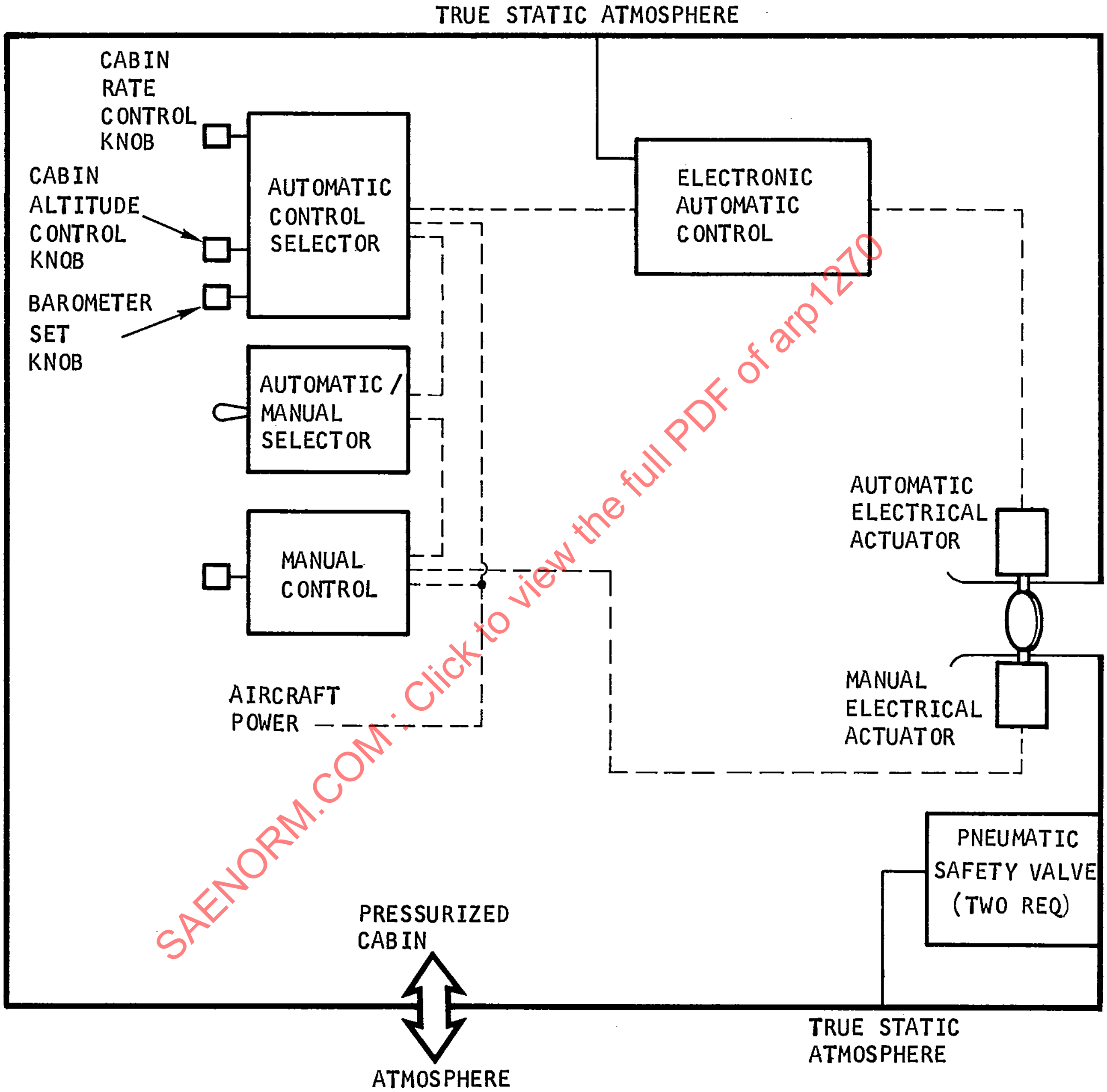


Figure 7. Electronic Cabin Pressure Control System

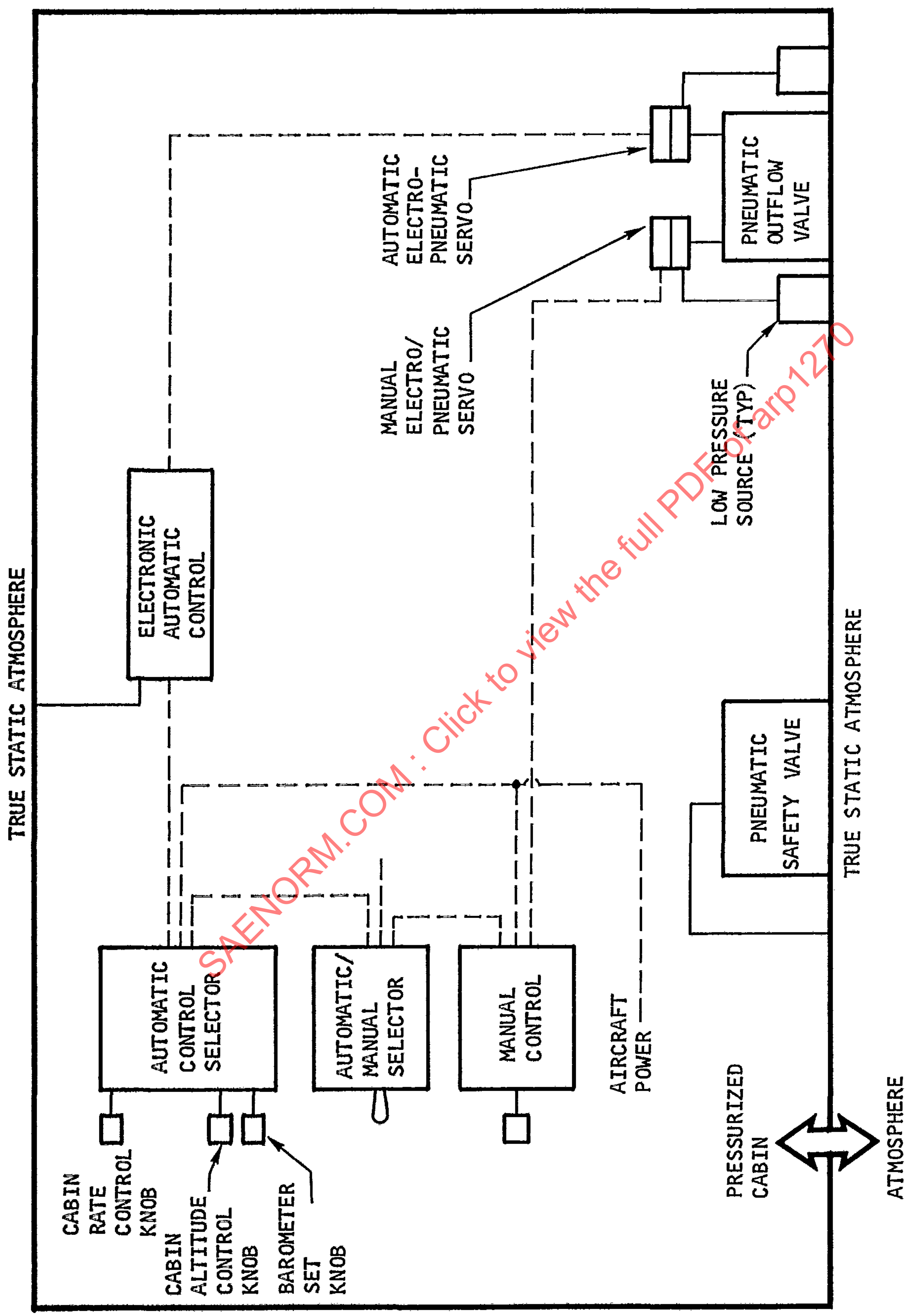


Figure 8. Electro-Pneumatic Cabin Pressure Control System

*where: W = Flow through outflow valve (lb/min)
CA = Flow coefficient times the geometrical area (sq in.)
P_i = Valve inlet pressure (in. Hg abs)
ΔP = Valve pressure drop (in. H_2O)
T_i = Valve inlet temperature (^oR)

EXAMPLE:

If cabin air inflow rate = 120 lb/min, cabin temperature = 70^oF, aircraft at SL on standard barometer day and the maximum allowable valve ΔP = 2 in. H_2O. What is required valve CA?

Substituting in formula above

$$120 = 8.76\ CA \sqrt{\frac{(29.92 + \frac{2}{13.6})(2)}{530}}$$

and therefore required CA = 40.7 sq in.

The above equation can be used to determine the cabin air outflow area which must be incorporated in unpressurized aircraft or helicopters to limit structural differential pressures during ascent or descent.

Refer to the section titled "SI Conversions and Abbreviations" for conversion of the above formula into SI units.

5.10.2 Relief Valve Sizing

Each positive pressure relief valve (safety valve) shall be designed to accommodate the maximum rate of flow delivered by the pressure source without an appreciable rise in the pressure differential. This requirement is interpreted to imply that each safety valve must be capable of limiting the differential pressure to the design value when functioning alone.

The maximum flow capacity of each of the safety valves should be based on the lowest altitude at which it is possible to reach the safety relief setting, assuming complete failure of the outflow valve(s). This could be any altitude between sea level and the flight level at which maximum pressure differential is obtained. It should be noted that the flow which must pass through the valve is increased when the airplane is climbing.

The negative pressure relief valve flow requirements should be based on an emergency rate of descent with an unpressurized airplane with zero cabin inflow. Careful consideration should be given to inlet pressure losses when arriving at final sizing.

5.10.3 Minimum Cabin Air Inflow Requirements for Rapid Descents

Figure 9 indicates the minimum cabin air inflow requirement for various size cabin volumes and for various descent rates. Airplane leakage values must be added to the minimum cabin air inflow to determine total inflow required.

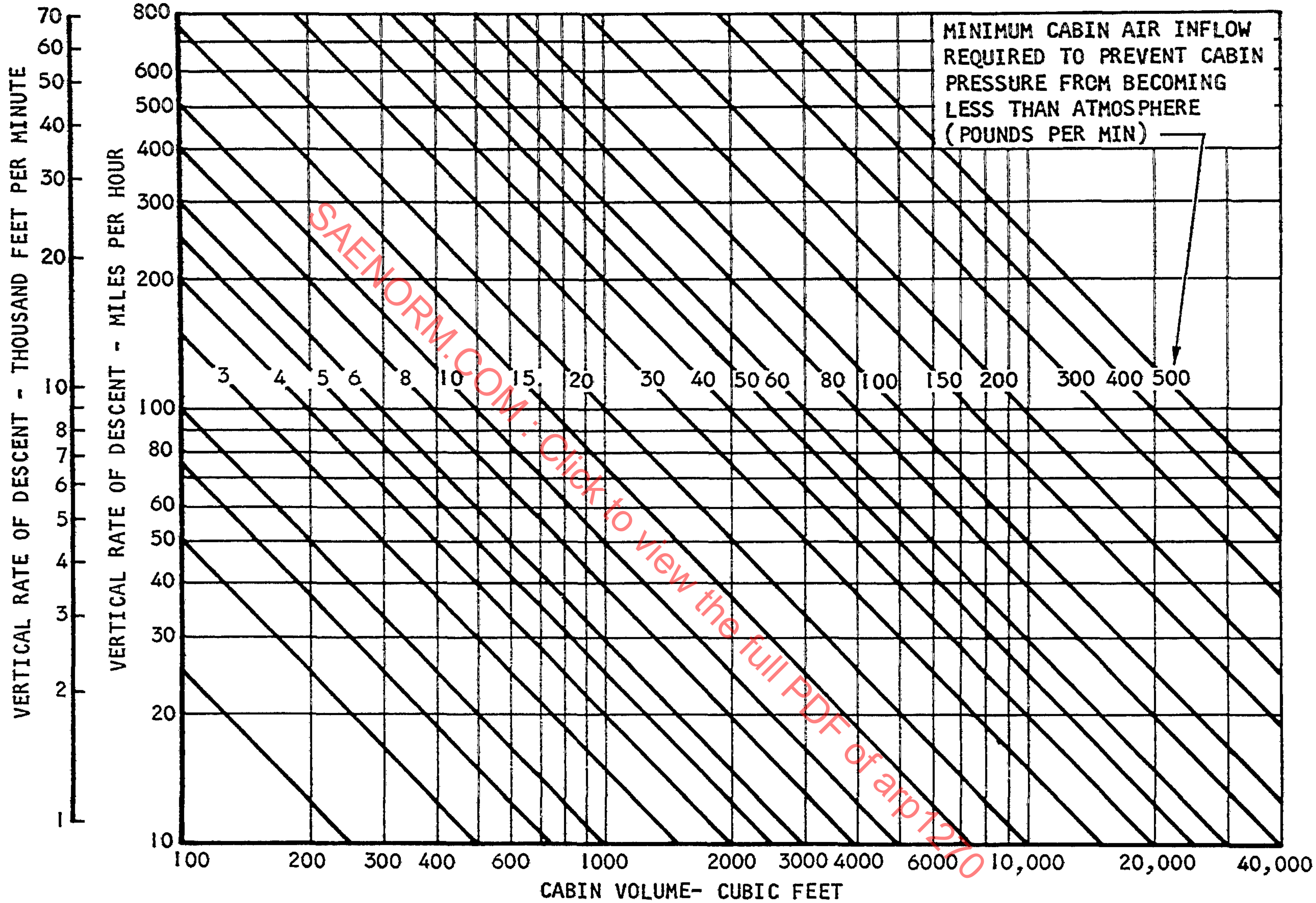
5.11 <u>Cabin Pressurization Control System Dynamic Analysis</u>

The internal pressure of an airplane cabin is controlled by maintaining a desired relationship between the airflows entering and leaving the cabin. To maintain the required relationship under varying airplane conditions necessitates a control system with a dynamic response compatible with the most rapid of the varying conditions. The dynamic analysis of a cabin pressurization system serves to exemplify the control system compliance with the specified performance requirements.

5.11.1 Control System Preliminary Analysis

The selection of an optimum control system for a specific airplane pressurization system ust be consistent with the constraints of that particular airplane. Once candidate systems are selected, a preliminary dynamic analysis is conducted to determine the feasibility of each of the systems meeting the response and stability performance criteria required.

*See also nomenclature section, Page 26.



NOTE: Refer to section titled "SI Conversions and Abbreviations" for conversion factors to SI units.

Figure 9. Inflow Requirements for Pressurization of the Cabin, Excluding Airplane Leakage

The primary analysis consists of describing the candidate systems mathematically, and examining the dynamic characteristics of the system through the use of various graphical techniques.

5.11.2 Control System Mathematical Model

The mathematical model is an analytical representation of the real system expressed in equations describing the physical processes involved. These equations express the relationships of air flows and pressures. Typical simplified expressions for an airplane cabin are:

1. $W_i = W_o + W_L + \frac{V}{RT}\frac{dPc}{dt}$

or

$P_c = \frac{RT}{V}\int (W_i - W_o - W_L)\ dt$

2. $W_L \approx K_L\ (P_c - P_A)$

3. $W_o = K_o\ CA_o\ P_c\ N$

4. $K_o\ CA_o = f(\theta)$

5. $N = f\left[\frac{P_c}{P_A}\right]$

6. $K_o = \frac{K}{\sqrt{T_c}}$ (T_c is assumed constant)

A diagramatical representation of a simplified proportional cabin pressure control system mathematical model is shown in Figure 10. In the proportional control system, the control valve position is proportional to the error magnitude between the commanded cabin pressure and the actual cabin pressure during steady state conditions. Theopen loop transfer functions for the control, actuator, position feedback and sensor, however always contain time variable terms which define their respective actions during transient conditions and affect, to varying degrees, the stability of the total system.

5.11.3 Control System Graphical Analysis

Once the mathematical model of a system has been determined, a stability and response analysis of the system may be accomplished. To accomplish this task, the open loop transfer functions of each

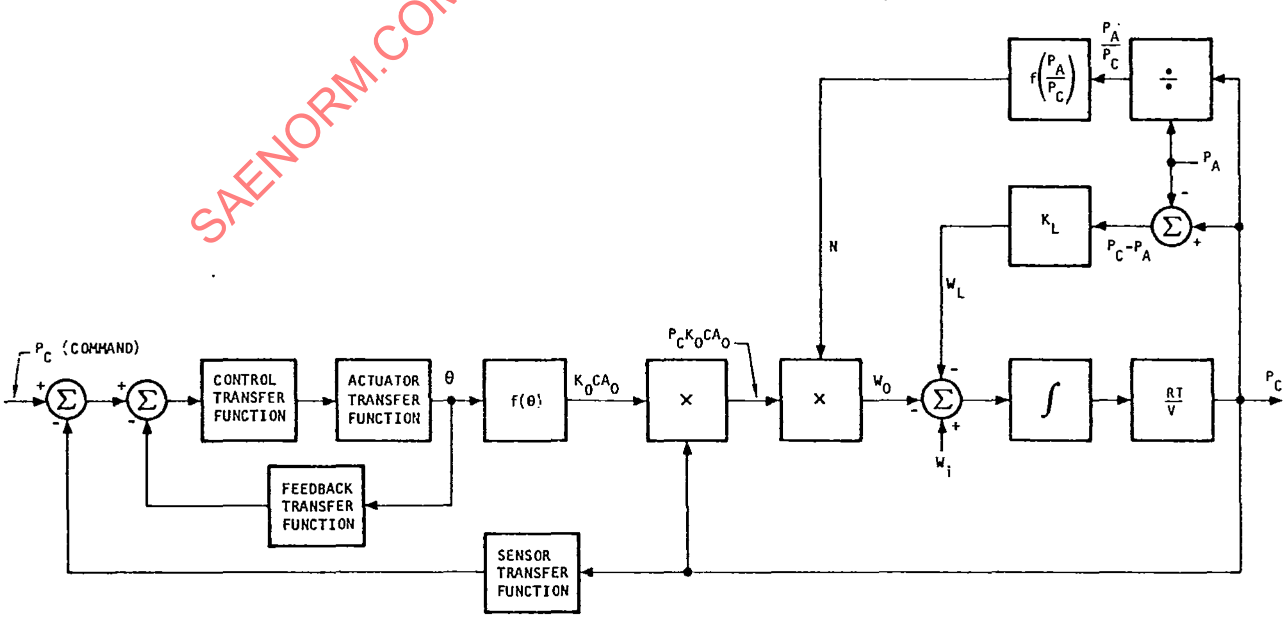


Figure 10. Mathematical Model Diagram

component of the system are determined. The open loop transfer function is defined as the ratio of the Laplace transforms of the output reaction to the input disturbance, expressed usually as a function of S.

The stability of the system is determined by comparing the open loop gain of the system expressed as a function of S vs the open loop phase lag of the system expressed in degrees. For the purpose of this analysis, jω is substituted for S and expressed in radians per unit time. The requirement for stability is that upon increasing ω, the total gain of the open loop goes to unity (0 db) before the phase angle of the open loop goes to -180 degrees. One method of determining the existence of this condition is through the use of an asymptotic plot of the system gain and phase angle vs S. One form of this plot is termed the Bode diagram (Figure 11).

The Bode diagram is constructed by plotting the gain of the system in decibels, and the phase angle in degrees against the frequency (S or jω) in radians per unit time, on semi-log paper. The gain in decibels is expressed as:

$$G\ (db) = 20 \log_{10} K,\ K \geq 1$$

$$G\ (db) = -20 \log_{10} \frac{1}{K},\ K < 1$$

The component gains, expressed in decibels, are added to produce the system gain. The steady-state gain is determined by equating jω to 0.

The open loop transfer function of the system is in the following general form.

$$TF = \frac{(U_{out})}{(D_{in})} =$$

$$K \left(\frac{S^{P}{}_{1}\ (1+a_1 S)(1+a_2 S)\ \ldots\ (1+a_m S)}{S^{P}{}_{2}\ (1+b_1 S)(1+b_2 S)\ \ldots\ (1+b_n S)} \right)$$

Examining the term (1+a S), it is noted that when $S \ll \frac{1}{a}$, 20 log (1+a S) equals 0. Furthermore, when $S \gg 1/a$, then 20 log (1+a S) has a slope of 20 db per decade of frequency.

$$\Delta G \left(\frac{db}{decade} \right) = 20 \log 10aS - 20 \log aS$$

$$\Delta G \left(\frac{db}{decade} \right) = 20$$

Likewise the terms $\frac{1}{1+bS}$ can be shown to yield

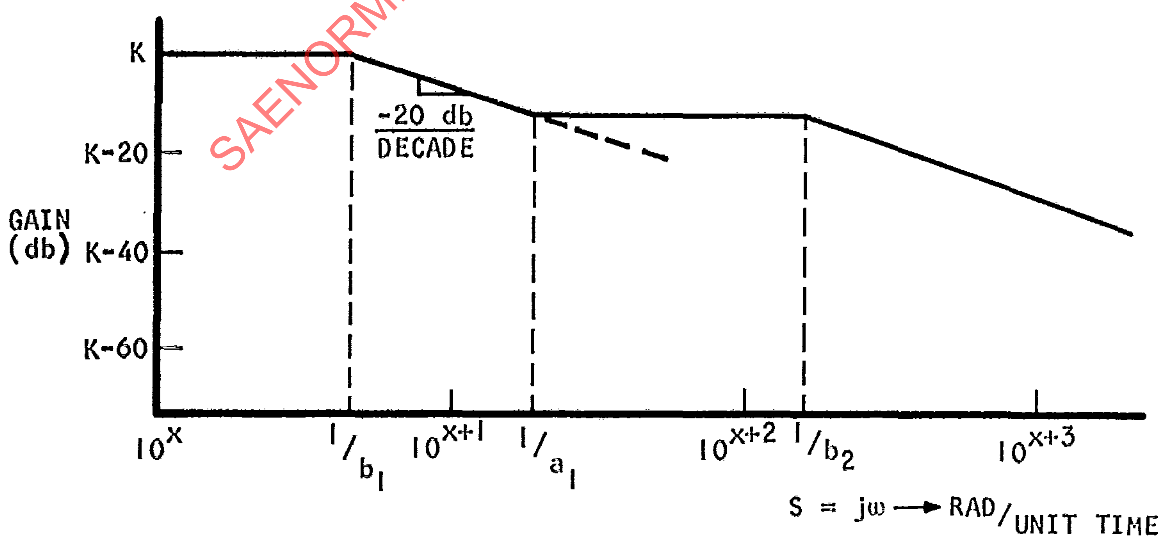


Figure 11. Bode Diagram of Gain

$$\Delta G \frac{db}{decade} = -20$$

The frequency at which the slope change caused by each term occurs is termed break frequency. The break frequency occurs at $S = \frac{1}{a}$, or $S = \frac{1}{b}$ respectively. The Bode plot of gain is constructed by the following steps.

(1) Determine system steady-state gain at S = 0 and plot this gain at low frequencies on the Bode diagram.

(2) Determine the gain change and break frequencies for each of the terms.

A system open loop transfer function in the following simplified form will plot as shown on diagram.

$$TF = K \frac{(1+a_1 S)}{(1+b_1 S)(1+b_2 S)} \quad \text{where}$$

$$B_1 > a_1 > b_2$$

The lines of the plot, in reality, represent the asymptotes of the actual plot of gain vs frequency.

The second portion of the Bode diagram is a plot of the phase angle vs frequency. Replacing S with jω results in a real and an imaginary portion of each of the terms of the transfer junction. The phase angle is the angle whose tangent is the imaginary portion divided by the real portion of each term.

$$\text{Phase angle} = \angle [1 + a(j\omega)] = \tan^{-1} \omega a$$

$$\text{Phase angle} = \angle \frac{1}{1 + b(j\omega)} = -\tan^{-1} \omega b$$

Substitution of values of ω result in values of phase angle for each term which are arithmetically accumulated to determine the total system open loop phase angle at that value of ω.

The measure of stability of a system is expressed as phase margin or gain margin. Phase margin is the difference between the phase angle, evaluated at the frequency at which the system open loop gain is unity (0 db), and -180 degrees. Gain margin is simply the amount by which the gain of the system may be increased before the system becomes unstable. Phase margins of 40 degrees and gain margins of 12 db are considered good design practice.

The response of the system is determined by solving for the closed loop transfer function of the system and writing the differential equation for any given input to the system. In most cases this is difficult and determining actual response in complicated systems is usually best accomplished with the help of analog computer simulation of the system.

5.11.4 Control System Computer Simulation

Once the feasibility of a particular control system approach has been determined through a preliminary dynamic analysis, the system is ready to be computer simulated. It is not unusual that the number of candidate system approaches have been drastically reduced by the preliminary analysis. The computer simulation serves to predict the detailed transient response and stability margin of the system with much greater ease than is possible with the preliminary analysis. The computer simulation offers the following advantages:

(1) Detailed system characteristics may be varied to explore their effects on the total system performance

(2) Non-linearities in system components may be simulated

(3) Effects of actual aircraft flight profiles and operational procedures may be simulated with results directly comparable to flight performance.

(4) Saturation levels of the system components may be simulated and the effects of the saturation levels on system performance determined.

The mathematical model is converted into an analog computer diagram, with additional computer circuitry employed to provide the system input variables. The logic associated with airplane cabin pressure selection can be simulated directly, as well as the expected airplane flight characteristics. The analog computer, extensively utilized for these types of simulations, simulates the system on a time continuous basis. A continuous system modeling program (CSMP) can also be used, however, to facilitate a digital computer simulation

Selection of analog or digital means of system simulation is optional and usually depends on equipment availability. Digital and analog computer simulations offer the following general advantages:

Digital
(1) Rapid initial program implementation
(2) Excellent documentation of results
(3) Higher attainable accuracy

Analog
(1) Capability of interface with actual control equipment
(2) Rapid evaluation of component characteristic variations

Computer simulation exemplifies that the system is capable of coping with all expected input disturbances while maintaining the cabin pressure within the specified performance requirements. The computer simulation furthermore, functions as a design tool, offering a fast effective method of determining where system changes are necessary and desirable.

5.12 Cabin Pressurization Control System Testing

Conventional methods of predicting cabin pressurization control system closed loop stability and performance under transient and abnormal conditions are best substantiated in the actual aircraft environment. This is impractical in all but limited applications and, therefore, effective means are required to conduct performance evaluations which closely simulate the aircraft environment. These tests normally include, but need not be limited to, steady-state isobaric control and differential control under the extremes of airflows and differential pressures, operation through the extremes of rate control, response to cabin inflow changes, effects of mode transfers, and effects of power interruption on electronic systems. Additional tests may be conducted depending upon individual concepts and designs used in the pressure control system.

The significance of the cabin volume can be seen in the simplified block diagram of a pneumatic system, Figure 12.

Cabin volume, perhaps the most difficult simulation to achieve, is one of the most important parameters in closed loop testing of a cabin pressurization system.

Tests of cabin pressure control systems to be used in small cabin volume aircraft are best tested by direct simulation of the aircraft volume, however, when testing systems for use in larger volume aircraft, direct simulation is difficult. Some of the means suited to obtain this simulation are described below:

5.12.1 Multiple Outflow Valve Installation

When the cabin pressurization system contains two or more outflow valves which control the exit air to maintain the desired level of pressurization, one valve can be used in the simulation of the cabin volume. To ensure representative performance evaluations, the scaling should be accomplished by application of the following basic equations:

$$Wis = Wia \times \frac{\eta s}{\eta a}$$

$$Vs = Va \times \frac{\eta s}{\eta a}$$

where:
- Wis = Cabin air flow of the simulation
- Wia = Cabin air flow of the aircraft
- ηs = Number of valves in the simulation
- ηa = Number of valves in the aircraft
- Vs = Volume of the simulation
- Va = Volume of the aircraft

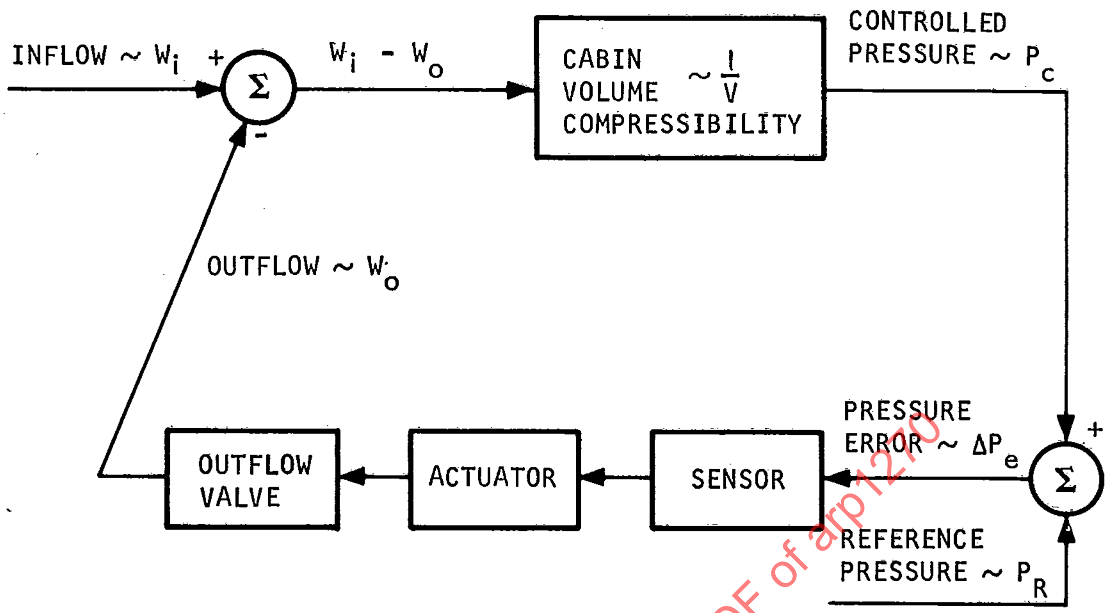


Figure 12. Pneumatic System Simplified Block Diagram

For example in an aircraft with two outflow valves, a direct simulation may be achieved using one outflow valve by halving the inflow and halving the volume.

5.12.2 Scaled Outflow Valve

The most useful means of simulating a large cabin volume when it is impractical to provide a direct simulation, is to scale the outflow valve effective discharge area throughout its operating stroke. This is done through a direct scaling of the aircraft volume to the volume available in the simulation by means of the following basic equations:

$$CAs = CAa \times \frac{Vs}{Va}$$

$$Wis = Wia \times \frac{Vs}{Va}$$

where: CAs = Effective outflow area of the simulation
CAa = Effective outflow area of the aircraft
Vs = Volume of the simulation
Va = Volume of the aircraft
Wis = Cabin air flow of the simulation
Wia = Cabin air flow of the aircraft

It should be recognized that scaling of the outflow effective area may result in dynamic changes to the outflow valve characteristics. Where affected characteristics would result in performance changes, consideration should be made for providing compensation in the simulation (e.g., matching of aircraft valve flow forces by adding the correct load torque to the simulated valve.)

5.12.3 Testing with Volumes Less Than a Scaled Simulation

When it is impossible or impractical to achieve a simulation that will provide the dynamics of the cabin volume as in Para. 5.12.1 or 5.12.2, system performance (but not stability) may still be assessed whenever the outflow valve slew rate is less than the maximum available