Dieter Scholz:

Aircraft Systems

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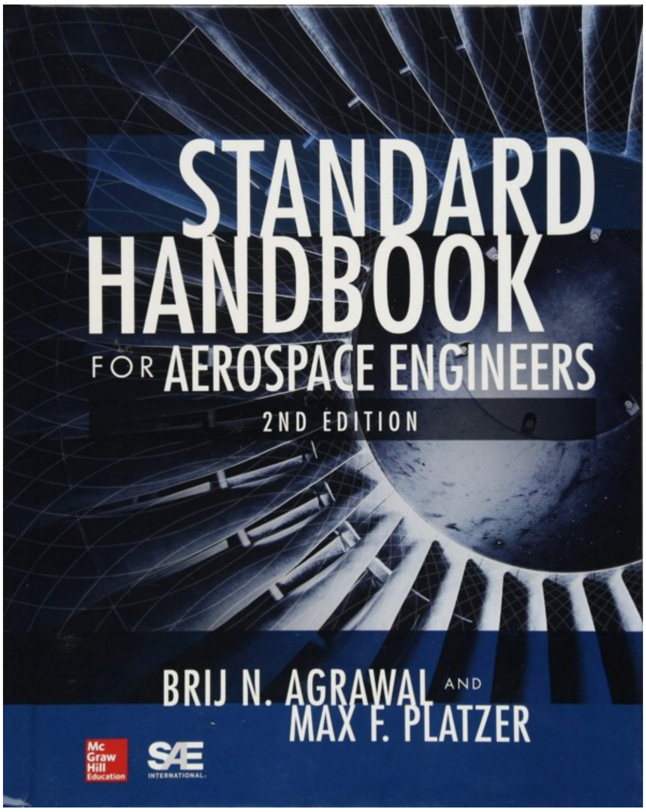

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Description

This resource presents theories and practices from more than 50 specialists in the many sub-disciplines of aeronautical and astronautical engineering. The book contains complete details on classic designs as well as the latest techniques, materials, and processes used in aviation, defense, and space systems.

Table of Contents: Futures of aerospace --- *Aircraft systems (SCHOLZ, Dieter)* --- Aerodynamics, aeroelasticity, and acoustics --- Aircraft performance --- Aircraft flight mechanics, stability, and control --- Avionics and air traffic management systems --- Aeronautical design --- Spacecraft design --- Astrodynamics --- Rockets and launch vehicles --- Earth's environment and space --- Attitude dynamics and control.

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Standard Handbook for Aerospace Engineers

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About SAE International

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Preface to the Second Edition

In the 15 years since the publication of the first edition of this handbook, many new developments have occurred, especially in the astronautics field. We have included them in this second edition, which is divided into three major areas.

In the first section the chief scientist of the NASA Langley Research Center presents his view of the likely aerospace developments in the coming years. The subsequent five sections provide the reader with an update of the major developments in aeronautics. These include major advances in predicting and measuring very complex flow phenomena due to the rapid increases in computing power in recent years. Therefore, parts on computational fluid dynamics, modern flow measuring techniques, computational aeroelasticity, and computational acoustics have been added to the coverage of classical aerodynamic analysis methods retained from the first edition. Similarly, a part on optimal control theory was added to the coverage of aircraft performance, stability, and control in order to draw attention to the progress achieved in this field. This is followed by a major revision of avionics coverage because, here again, major advances have occurred. Also, in this section new parts on air traffic management have been added. Two sections retained with only minor changes cover aircraft systems and aircraft design.

The subsequent six sections provide the reader with an update of the major developments in astronautics. The sections titled Astrodynamics, Rockets and Launch Vehicles, and Earth's Environment and Space have been retained from the first edition with an updating of the material. Three new sections titled Spacecraft Systems, Spacecraft Subsystems, and Spacecraft Design have been added. The Spacecraft Systems section covers satellite missions, test and product certification of space vehicles, space safety engineering and design, and spacecraft for human operation and habitation. The Spacecraft Subsystems section covers attitude dynamics and control, observation payloads, spacecraft structures, satellite electric power subsystems, systems engineering requirements, independent verification and validation, software safety for aerospace systems, thermal control, and communications. Spacecraft Design covers the spacecraft design process, a design example, concurrent engineering, and small spacecraft.

We would like to recognize the contributions of the editor of the first edition, Mark Davies. We are greatly indebted to the contributors of the new sections in the second edition for their efforts and cooperation and to the authors of the sections retained from the first edition for updating their work. Also, we express our special thanks to the Editorial Director—Engineering at McGraw-Hill, Robert Argentieri, and the Senior Project Manager at Cenveo Publisher Services, Sonam Arora, for their outstanding support during the preparation and production of this book. And then we are especially indebted to two wonderful ladies, our wives Shail Agrawal and Dorothea Platzer, who made it all possible through their love and understanding.

Brij N. Agrawal
Max F. Platzer
Editors

Preface to the First Edition

The Standard Handbook for Aeronautical and Astronautical Engineers represents the efforts of many people working toward the common goal of amalgamating aeronautical and astronautical engineering into a single handbook. This is the first publication of such a book. A handbook on only astronautical was published by the same publishers in the early 1960s, which now represents a fascinating insight into the minds of those early pioneers.

The challenge to put the aeronautical and astronautical together was considerable. Although they overlap in so many ways, they also have many differences that needed to be addressed. The publisher's brief was for a book that successfully brought about this combination and that would be of value to professional engineers and engineering students alike. It must, therefore, cover something of every aspect of the vast spectrum of knowledge and methods that is aerospace engineering. Working between the covers of a book that can be carried by an unaided individual, of average strength, has meant that much cannot be included.

At an early stage in the *Handbook*'s development, I decided that there would not be sufficient pages available to do justice to the military aspects of aerospace engineering. Consequently, the reader will not find many references to the military for the aeronautical and, similarly, for astronautical observation. Perhaps 75% of the book's contents would be on most engineers' list of essential engineering; the remaining 25% is there because of the section editors' and my opinions and prejudices.

The *Handbook* opens with a look at what the future may hold for the development of aeronautical and space systems. This sets the scene for what is to follow. Before addressing these issues directly, there are five sections on basic engineering science and mathematics that are the foundation of aerospace operations and design. Applications have been excluded, for the most part, from these sections to emphasize their generality. In the specialist section, wherever possible, aeronautical and space issues have been addressed in the same section, as in Aerospace Structures (Section 9) and Avionics and Astrionics (11); elsewhere, they have been divided, as in Aeronautical Propulsion (7) and Rockets and Launch Vehicles (8). Subsystems for aircraft are covered in a single section (12), whereas for spacecraft, they are part of Section 15. Because aircraft design is more standardized and mature, it occupies its own section (13). Astrodynamics (14) and Spacecraft (15) are unique to space, whereas the discussions on safety (17) and maintenance (18) are unique to aircraft.

Due to its limited size, the book cannot give a definitive account of any specific area. Thus, experienced aerodynamicists may not find everything of interest in the aerodynamics section; nevertheless, they will find much of interest, for example, in the structures sections—the very structures that interact with the aerodynamic forces.

In this, the first edition, I feel that only the first stage in the journey to provide a comprehensive handbook has been made. Lionel Marks' *Standard Handbook for Mechanical Engineers*, in print through many editions for almost a century, is a reference that has been invaluable to that discipline.

It is my hope that one day I will have made a similar contribution to aeronautical and astronautical engineering.

For the present, I thank all of those who have helped in this endeavor, beginning with my commissioning editor, Shelley Carr, with whom at times I have been in daily correspondence; she never wavered in her confidence and support for me, or if she did, I never knew. Then, I thank all of the section editors, the contributors, all of their colleagues and students who have helped, all of the institutes and companies that employ them, and my own institution, the University of Limerick, and my family: Judith, Elisabeth, and Helena.

Mark Davies
Editor

Contents

SECTION 2

Aircraft Systems

Dieter Scholz

2.1 Introduction

Aircraft Systems—General

What Are Aircraft Systems? Broadly speaking, an aircraft can be subdivided into three categories:

1. The airframe (the aircraft structure)
2. The power plant (the engines)
3. The aircraft systems (the equipment)

This Section deals with the last of these categories.

The airframe provides the aircraft with its (relative) rigidity. It also enables the generation of lift through its aerodynamic shape. A glider flies without a power plant, but in order to maintain weather-independent sustained level flight, a power plant is necessary to produce thrust to overcome the drag.

The airframe and power plant might seem to be all that is needed, but this is not so. Even the earliest aircraft needed more. Some means to steer the aircraft (flight controls) and to handle it on the ground (landing gear) were needed. These aircraft systems play a key role today and must be considered in the very early stages of aircraft design. A fuel system was also needed from the beginning of the history of powered flight. With aircraft flying longer distances, navigation and communication systems became important; with aircraft flying higher and taking passengers on board, cabin systems such as air conditioning and oxygen systems were introduced.

Above is given a general idea of what aircraft systems are. A more rigorous definition of the term is given further.

Significance of Aircraft Systems

Aircraft systems account for one-third of the aircraft's empty mass. Aircraft systems have a high economic impact: more than one-third of the development and production costs of a medium-range civil transport craft can be allocated to aircraft systems, and this ratio can be even higher for military aircraft. The price of the aircraft is driven in the same proportion by aircraft systems. Aircraft systems account for roughly one-third of the direct operating costs (DOC) and direct maintenance costs (DMC).

Historical Trends

Aircraft silhouettes and general design concepts have been stable since the 1960s. Nevertheless, remarkable progress has been made since that time. Just as aerodynamics, structures, and power plants have been optimized, aircraft systems have been gradually improved in economics, reliability, and safety. This has been made possible by constant evolution and optimization through inservice experience, research, and development and by employment of new technologies.

Probably the most important factor in the changes has been made by digital data processing. Today computers are part of almost every aircraft system in larger aircraft. Computers also play a key role in the design and manufacturing process of aircraft systems. The evolution of aircraft systems has not come to an end yet. Modern achievements in computer technology will continue to make their way into aircraft.

Striving for improved safety, economics, and passenger comfort will demand even more sophisticated technologies and complexity. The airlines have been reluctant to accept the ever-increasing complexity, since it does not make troubleshooting the aircraft any easier. The aviation industry has taken the approach that technology has to buy its way onto the aircraft—i.e., only if new technologies can prove their overall benefit will they be considered in new aircraft design.

The separate tasks of the structure, the engines, and the systems are being more and more integrated to handle the tasks together. Here are some examples:

- Electronic flight control systems stabilize a fighter aircraft with an unstable layout or stabilize aircraft structural or rigid body modes.
- A gust load alleviation system as part of the flight control systems helps reduce the design loads for the wing structure.
- A highly reliable yaw damper system enables the aircraft to be built with a fin smaller than would otherwise be required.
- Engine parameters are changed in accordance with air conditioning demands.

To achieve an overall optimum in aircraft design, it is no longer possible to look at the structure, the engines, and the aircraft systems separately. Today's challenge lies in optimizing the aircraft as a whole by means of multidisciplinary design optimization (MDO).

The Industry

Aircraft systems are defined by the aircraft manufacturer. This commonly takes place in joint teams with engineers from specialized subcontractors. The subcontractors work on the final design, manufacture the system or component, and deliver their parts to the aircraft manufacturer's final assembly line. The trend is for aircraft manufacturers to select major subcontractors who are made responsible for designing and manufacturing a complete aircraft system. These subcontractors may even become risk-sharing partners in the aircraft program. Aircrafts are maintained by dedicated maintenance organizations. Maintenance is done on and off aircraft. Off-aircraft maintenance is performed on aircraft components in specialized shops.

Scope of This Section

Section 2 provides background information and describes the general principles of transport category aircraft systems. The Airbus A321 (Figure 2.2) from the family of Airbus narrow-body aircraft is used to provide an example of the systems under discussion. *At no time should the information given be used for actual aircraft operation or maintenance. The information given is intended for familiarization and training purposes only.* Space in this handbook is too limited for all aircraft systems to be covered in depth. For some aircraft systems only the definition is given and the reader is referred to other parts of the handbook that also deal with the subject. For other aircraft systems the definition is given together with selected views on the Airbus A321. Emphasis is put on selected major mechanical aircraft systems. The References and Further Reading show the way to actual design work and detailed studies.

Definitions

The term *system* is frequently used in engineering sciences. In thermodynamics, for example, a system is characterized by its defined boundary. The definition of the term with respect to aircraft is more specific.

The World Airlines Technical Operations Glossary (WATOG) defines:

- *System:* A combination of inter-related items arranged to perform a specific function
- *Subsystem:* A major functional portion of a system, which contributes to operational completeness of the system

The WATOG also gives an example together with further subdivisions of the system and subsystem:

- *System:* auxiliary power unit
- *Subsystem:* power generator
- *Component:* fuel control unit
- *Subassembly:* valve
- *Part:* seal

Note that these definitions refer to civil aircraft. With respect to military aircraft, instead of *aircraft systems* the term is *aircraft subsystems*. In the example above, the auxiliary power unit hence would be considered a subsystem.

In dealing with aircraft systems, all categories of aircrafts need to be considered. ICAO defines:

- *Aircraft:* Any machine that can derive support in the atmosphere from the reaction of the air (ICAO Annex 2)
- *Aircraft category:* Classification of aircraft according to specified basic characteristics, e.g., aeroplane, glider, rotorcraft, free balloon (ICAO Annex 1)

Combining the above definitions, a definition for aircraft systems might be:

- *Aircraft system:* A combination of interrelated items arranged to perform a specific function on an aircraft

This section deals with aircraft systems in powered heavier-than-air aircraft. Although aircraft systems in gliders, rotorcrafts, and free balloons have to take into account the specifics of their respective categories, they are not fundamentally different from aircraft systems in aeroplanes.

Breakdown

Aircraft systems are distinguished by function. It is common practice in civil aviation to group aircraft systems according to Specification 100 of the Air Transport Association of America (ATA) (ATA 100), which thoroughly structures aircraft documentation. According to ATA 100,[1] aircraft

[1]Recently ATA 100 became part of the new ATA 2200. ATA 2200 has introduced minor changes and updates to the definitions of aircraft systems. This text uses the well-established ATA 100 and presents differences to ATA 2200 in footnotes.

Identifier	Name of system
21	air conditioning
22	auto flight
23	communications
24	electrical power
25	equipment/furnishings
26	fire protection
27	flight controls
28	fuel
29	hydraulic power
30	ice and rain protection
31	indicating/recording systems
32	landing gear
33	lights
34	navigation
35	oxygen
36	pneumatic
38	water/waste
49	airborne auxiliary power

[a]Not included in this table are Chapters 37, 41, 45, and 46 from ATA 100, which are not of relevance here. Also not included here are new Chapters 44 and 50 from ATA 2200.

Table 2.1 Aircraft Systems[a] (ATA 100)

equipment is identified by an equipment identifier consisting of three elements of two digits each. The identifier 29-31-03 points to system 29, subsystem 31, and unit 03. The aircraft systems— or, in ATA terms, *airframe systems*—are listed in Table 2.1 together with their system identifiers. It is common practice to refer to just the system identifier *ATA 28,* instead of to the "fuel system." Furthermore, *Chapter 28* (from ATA 100) is often referred to, because that is the chapter allocated to the fuel system in any aircraft documentation showing ATA conformity.

Autopilot, communications, navigation, and indicating/recording systems (ATA 22, 23, 34, 31 [, 44, 45, 46]) are electronic systems, known in aviation as *avionic systems,* and are characterized by processing information (compare with SAE 1998).

Other systems provide fuel, power, and essential comfort to crew and passengers. These non-avionic systems are the *general* or *utility systems.* Today there is an increase in the number of electronic control units within the utility systems; nevertheless, the primary purpose of these systems remains some kind of energy transfer (Moir and Seabridge 2001).

Secondary power systems include the nonpropulsive power generation and transmission. They include electrical power, hydraulic power, pneumatic, and auxiliary power (SAE 1998) (ATA 24, 29, 36, 49). Secondary power systems provide power to other aircraft systems.

The *environmental control system* (ECS) is an engineering system that maintains the immediate environment of an organism within defined limits of temperature, pressure, and gaseous composition suitable for continuance of comfort and efficiency (AGARD 1980). The air conditioning system and oxygen system (ATA 21, 35) are assigned these tasks.

Other aircraft systems are grouped and assigned a specific name often without a formal definition.

Hydraulic systems comprise all systems that apply hydraulic power. In general, these are hydraulic power, flight controls, and landing gear (ATA 29, 27, 32).

Electric systems comprise all systems that apply electric power. In general, these are electric power (ATA 24) and all systems with major electrical consumers. Electrical systems are characterized by electrical power generation, distribution, and consumption and have to be distinguished from avionic systems.

Pneumatic systems comprise all systems that apply pneumatic power. In general, these are pneumatic and other systems with pneumatic components (ATA 36, 21, 30).

Cabin systems[2] comprise all systems with an impact on the cabin of the aircraft and hence with an influence on the passenger (ATA 21, 25, 35, 38, and partially 23, 26, 31, 33).

These groupings depend to a certain extent on the system technologies applied in the aircraft being considered.

Certification

After one or several prototype aircraft are designed and manufactured, they go through a series of *certification tests* in order to show compliance with the *certification requirements*. Compliance with the requirements may be shown by analysis, ground, or flight test, depending on the requirements or negotiations with the *aviation administration*. System tests are a substantial part of the certification program. In Europe, certification of large aeroplanes is based on the Joint Aviation Requirements (JAR-25), and in the United States it is based on the Airworthiness Standards: Transport Category Airplanes (FAR Part 25). Large aeroplanes are those aircraft with a maximum takeoff mass of more than 5,700 kg. JAR and FAR are very similar; the basic code for JAR-25 is FAR Part 25, and further harmonization of the requirements is in progress. The certification of one or several prototype aircraft leads to a *type certificate* being issued. Aircraft in series production have to show *airworthiness* and *conformity with the prototype aircraft*. In service the aircrafts have to be maintained according to an agreed maintenance schedule to prove continuous airworthiness.

JAR-25 and FAR Part 25 are grouped into several subparts (the following is based on JAR-25).

Subpart F, "Equipment," contains many requirements for aircraft systems.

Subpart E, "Power plant," contains requirements for power plant-related systems.

Also Subpart D, "Design and Construction," contains requirements for aircraft systems.

Subpart J, "Gas Turbine Auxiliary Power Unit Installation," contains requirements for airborne auxiliary power—i.e., the auxiliary power unit (APU).

General information on aircraft systems can be found in section 1301 "Function and installation" and section 1309 "Equipment, systems and installations" of JAR-25 and FAR Part 25. Section 1309 provides information on safety requirements, loads, and environmental conditions. Table 2.2 provides access to the certification requirements for large airplanes when specific information related to a particular aircraft system is needed.

Interpretative material to most paragraphs is provided:

- FAR: Advisory Circulars (AC) (especially in AC 25-17 and AC 25-22)
- JAR: Advisory Circular Joint (ACJ) (ACJ-25) and Advisory Material Joint (AMJ) (AMJ-25)

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[2]Following the new ATA 2200, "Cabin Systems (ATA 44)" are defined as "Those units and components which furnish means of entertaining the passengers and providing communication within the aircraft and between the aircraft cabin and ground stations. Includes voice, data, music and video transmissions."

Identifier name of system	Applicable sections
21 Air conditioning	831–833: Sections under the heading "Ventilation and heating" 841–843: Sections under the heading "Pressurisation" 1461: Equipment containing high energy rotors
22 Auto flight	1329: Automatic pilot system 1335: Flight director systems
23 Communications	1307: Miscellaneous equipment (radio communication) 1457: Cockpit voice recorders
24 Electrical power	1351: General 1353: Electrical equipment and installations 1355: Distribution system 1357: Circuit protective devices 1359: Electrical system fire and smoke protection 1363: Electrical system tests
25 Equipment/furnishings	771–793: Sections under the heading "Personnel and cargo accommodations" 819: Lower deck service compartments (including galleys) 1411: General (under heading safety equipment) 1413: Safety belts 1415: Ditching equipment 1421: Megaphones
26 Fire protection	851–867: Sections under the heading "Fire protection" 1181–1207: Sections under the heading "Powerplant fire protection" 1307: Miscellaneous equipment (portable fire extinguishers) A1181–A1207: Sections related to APU fire protection
27 Flight controls	671–703: Sections under the heading "Control systems"
28 Fuel	951–981: Sections under the heading "Fuel system" 991–1001: Sections under the heading "Fuel system components" A952–A999: Sections related to the APU fuel system
29 Hydraulic power	1435: Hydraulic systems
30 Ice & rain protection	1307: Miscellaneous equipment (including windshield wiper) 1416: Pneumatic de-icer boot system 1419: Ice protection
31 Indicating/recording systems	1303: Flight and navigation instruments 1305: Powerplant instruments 1321: Arrangement and visibility 1331: Instruments using a power supply 1333: Instrument systems 1337: Powerplant instruments
32 Landing gear	721–X745: Sections under the heading "Landing gear"

TABLE 2.2 Selected Certification Requirements for Aircraft Systems Based on JAR-25

Identifier name of system	Applicable sections
33 Lights	812: Emergency lighting 1322: Warning, caution, and advisory lights 1381: Instrument lights 1383: Landing lights 1385, 1387, 1389, 1391, 1393, 1395, 1397: Position lights 1401: Anti-collision light system 1403: Wing icing detection lights
34 Navigation	1307: Miscellaneous equipment (radio navigation) 1323: Airspeed indicating system 1325: Static pressure system 1326: Pilot heat indication system 1327: Magnetic direction indicator 1459: Flight recorders
35 Oxygen	1439: Protective breathing equipment 1441: Oxygen equipment and supply 1443: Minimum mass flow of supplemental oxygen 1445: Equipment standards for the oxygen distributing system 1447: Equipment standards for oxygen dispensing units 1449: Means for determining use of oxygen 1450: Chemical oxygen generators 1451: Fire protection for oxygen equipment 1453: Protection of oxygen equipment from rupture
36 Pneumatic	X1436: Pneumatic systems—high pressure 1438: Pressurisation and low pressure pneumatic systems
38 Water/waste	1455: Draining of fluids subject to freezing X799: Water systems
49 Airborne auxiliary power	Paragraphs in Subpart J—Gas turbine auxiliary power unit installations

Table 2.2 Selected Certification Requirements for Aircraft Systems Based on JAR-25 (*Continued*)

Safety and Reliability

Safety and reliability considerations of aircraft systems are an integral part of the safety and reliability considerations of the whole aircraft. Modern sophisticated aircraft depend very much on the proper functioning of their aircraft systems, so that safety and reliability considerations of aircraft systems have become highly important in their own right. For this reason an aircraft systems-specific approach to the topic is presented here.

Safety is a state in which the risk is lower than a permissible risk. The risk is defined by the probability of a failure and the expected effect.

The *effect* of failure describes the consequences of the failure (damage or injury).

The *probability of failure*, $F(t)$, is equal to the number of failures within a given period of time divided by the total number of parts in a test.

The *safety requirements* for aircraft systems are stated in section 1309 of the certification requirements JAR-25 and FAR Part 25 and are listed in Table 2.3.

Effect on aircraft and occupants	Normal	Nuisance	Operating limitations Emergency procedures	Significant reduction in safety margins Difficult for crew to cope with adverse conditions Passenger injuries	Large reduction in safety margins Crew extended because of workload or environmental conditions Serious injury or death of small number of occupants	Multiple deaths, usually with loss of aircraft
Category of effect Probability of a failure according to JAR-25 (per flight hour)	Minor Frequent 10^{0}–10^{-2}	Minor Frequent 10^{-2}–10^{-3}	Minor Reasonably probable 10^{-3}–10^{-5}	Major Remote 10^{-5}–10^{-7}	Hazardous Extremely remote 10^{-7}–10^{-9}	Catastrophe Extremely improbable $< 10^{-9}$

Source: ACJ-25.

Table 2.3 Safety Requirements for Large Airplane's Systems

The probability of a failure in a system increases with the time period of operation and is specified for an operation time of one flight hour (FH). Obviously, the higher the effect of a failure is on aircraft operation, passengers, and the aircraft itself, the lower the permissible probability of such a failure has to be.

The *reliability* is the probability of survival, $R(t)$. It is an item's ability to fulfill defined requirements for a specific period of time under specified conditions. A statement referring to the reliability of a system can only be made if the failure criteria are precisely defined.

The reliability or *probability of survival*, $R(t)$, can also be defined as the number of parts surviving within a given period of time divided by the total number of parts in a test:

$$R(t) + F(t) = 1$$

Although referring to the reliability $R(t)$, mostly the value of the probability of failure $F(t)$ is given (10^{-7}) because the reliability yields values more difficult to handle (0.9999999).

The *hazard rate function*, $z(t)$, is a measure of the probability that a component will fail in the next time interval, given that it has survived up to the beginning of that time interval. If the hazard rate function is constant (which is often assumed), it is called the *failure rate*, λ Failure rates of mechanical components are listed in Rome (1985), and failure rates for electric and electronic equipment can be estimated using MIL-HDBK-217. The failure rate has units of one per flight hour (1/FH). The inverse of the failure rate, called the mean time between failures (MTBF), is often used in reliability and maintenance circles.

$$\text{MTBF} = 1/\lambda$$

The *failure to removal ratio* (FTRR) is a maintenance quantity. It shows the ratio of faults found in a component during a shop visit, divided by the number of component removals. Unfortunately, the FTRR is especially low in case of electrical components (0.6–0.7) and electronic components (0.3–0.4). Hydraulic components (0.8–0.9) and mechanical components (1.0) show better values. The product of MTBF and FTRR yields the maintenance cost driver, the *mean time between unscheduled removals* (MTBUR).

$$\mathrm{MTBUR} = \mathrm{MTBF} \cdot \ \mathrm{FTTR}$$

The reliability and the probability of failure can be calculated from the failure rate:

$$R(t) = e^{-\lambda t}, \ F(t) = 1 - e^{-\lambda t}$$

For low failure rates, which are common in aviation, the probability of failure calculated for a period of one hour ($F(t)$/FH) equals almost exactly the failure rate, λ.

Systems are a combination of many components either in parallel, in series, or in a combination of both. The reliability of a *series system* is equal to the product of is component values.

$$R_S(t) = R_1(t) R_2(t) R_3(t) \ldots$$

The failure rate of a series system is approximately the sum of the failure rates of its (reliable) components.

$$\lambda_S \approx \lambda_1 + \lambda_2 + \lambda_3 \ \ldots$$

The probability of failure of a *parallel system* is equal to the product of is component values.

$$F_P(t) = F_1(t) F_2(t) F_3(t) \ldots$$

The failure rate of a parallel system is approximately the product of is (reliable) component values.

$$\lambda_P \approx \lambda_1 \lambda_2 \lambda_3 \ \ldots$$

Systems can be depicted by *reliability block diagrams* (RBDs). The analysis of large systems is carried out in successive stages. At each stage a small number of components connected either in parallel or in series is combined with equations as shown above. In this way the complexity of the system can be reduced step by step. The *fault tree analysis* (FTA) is an alternative method to deal with complex systems. Parallel systems are combined by an OR gate symbol. Series systems are combined by an AND gate symbol. Top events are shown in a rectangle and basic failure causes are shown in circles. Software tools exist that support a FTA or the analysis of a RBD. Systems might show cross-linkages so that some units are in more than one subsystem. One way of dealing with this problem is to use a theorem on conditional probability or to apply a truth table (Davidson 1988).

These approximate equations for series and parallel systems are quite useful in day-to-day business. The last equation also shows the ability of parallel systems to achieve low failure rates and thus high reliability. For example, three components combined in parallel with a failure rate of 10^{-3} 1/FH each, yield an overall failure rate of 10^{-9} 1/FH. This is a failure rate that could not have been achieved by a single component no matter how carefully this component was manufactured and tested. This thought leads us to the concept of redundancy, which is so typical in safety critical aircraft systems.

Redundancy is the existence of more means for accomplishing a given function than would simply be necessary. It is divided into

- Homogeneous redundancy (the multiple means are identical) and
- Inhomogeneous redundancy (the multiple means are of different type)

Inhomogeneous redundancy is divided into:

- Dissimilar redundancy or
- Diversitary redundancy

Safety-critical aircraft systems often show *triplex* subsystems. The system architecture of safety-critical computers may be even of *quadruplex* or *duo duplex* type.

The subsystems of a system with built-in redundancy may all work together. If one subsystem fails, the others will just have to cope with a somewhat higher load. These systems are called *active-active* systems. Other systems may be of the *activestandby* type and need to perform a changeover in case of a failure. If the standby subsystem is constantly waiting to be activated, it is on *hot standby;* otherwise it is on *cold standby.* The changeover should not be dependent on a changeover unit, because this unit with its own limited reliability might fail and prevent the changeover. If an active-standby concept is applied, the subsystems should take turns doing the job. This could be achieved with a planned changeover before every takeoff. If the same subsystem stays in standby all the time, it may show an (undetected) *dormant failure* and hence will not be able to take up the job in case of failure of the first subsystem. Systems with a potential of dormant failures need regular maintenance checks and should be avoided.

An assumption has been made in the calculation of parallel systems that the failures of individual subsystems are independent of each other, that is, that two or more subsystems do not fail simultaneously from precisely the same cause (except purely by chance). However, most systems have the potential of having more than one failure due to a common cause. These failures are called *common cause failures* (CCFs). They tend to arise from errors made during design, manufacture, maintenance, operation, or environmental effects. For example, loss of power supply could cause both a running and a standby pump to fail (design error), or an empty fuel tank could cause all engines to quit (error in operation). Because these failure modes may appear to be outside the system being assessed, they can easily be overlooked, leading to too-optimistic assessments. Methods to avoid common cause failures in the design stage are the application of

- Inhomogeneous redundancy (see above)
- Segregation in the rooting of redundant wires, pipes, and ducts
- Separation of redundant components
- Placement of safety-critical components in safe areas
- Design of redundant components or software programs by independent teams with different (software) tools

An aircraft should not only be safe to fly, it should also show very few errors that need the attention of maintenance personnel. In this respect we face a problem with high safety requirements. High safety requirements lead to the application of redundancy and hence more subsystems. The probability of a failure leading to the loss of the overall function can be reduced by redundancy, but the probability of occurrence of any failure anywhere in the system is increased. Two subsystems with a failure rate of 10^{-3} 1/FH each yield an overall probability of failure of about 10^{-6} and a probability of any failure of $2 \cdot 10^{-3}$ (based on a 1-hour operation). Three subsystems yield an overall probability of failure of 10^{-9} and a probability of any failure of already $3 \cdot 10^{-3}$. The level of safety during flight can only be achieved if all subsystems work properly before takeoff, but, as we have seen, the probability for any failure increases with an increased number of subsystems. These thoughts lead to what is called availability and dispatch reliability.

The *steady state availability* is defined as the probability that a system will be available when required, or as the proportion of total time that the system is available for use. Therefore, the availability of a system is a function of its failure rate λ and of its repair rate $\mu = 1/\text{MTTR}$, where MTTR is the mean time to repair:

$$A_{\text{SS}} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{\mu}{\lambda + \mu}$$

The *instantaneous availability,* or probability that the system will be available at time t, is

$$A_I = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}$$

Often it is more revealing to consider system unavailability, $U = 1 - A$. The instantaneous availability of an aircraft at the moment of dispatch from the gate is called *dispatch reliability.* Dispatch reliability, for technical reasons, primarily depends on the combined dispatch reliability of the aircraft systems. The airlines monitor their fleets' dispatch reliability very carefully because high *dispatch unreliability* leads to delays and cancellations of flights and incurs delay and cancellation costs (see below). Dispatch reliability depends on the maturity of an aircraft program and is on the order of 0.99. A method to increase dispatch reliability is the introduction of *built-in test equipment* (BITE) into electronic systems. Though this adds complexity and might result in spurious failure indications, it can greatly reduce maintenance times by providing an instantaneous indication of failure location. Another method is to provide *extra redundancy* above the level required for safety reasons. This would than allow to dispatch with one subsystem inoperative. Components that are not needed for takeoff may be known as *flying spares.* The pilot gets a clear indication about which subsystems or components need to be available at takeoff from the *minimum equipment list* (MEL), written by the airline on the basis of the master minimum equipment list (MMEL) provided by the manufacturer and approved by the authorities.

Reliability assurance during the aircraft system design applies a couple of different methods, including:

- Drawing a fault tree for a *fault tree analysis* (FTA) (see above) starts from consideration of system failure effects, referred to as top event. The analysis proceeds by determining how these can be caused by lower-level failures. In this way it is a top-down approach.
- The *reliability apportionment* breaks an overall system reliability requirement down into individual subsystem reliabilities. This is common in large systems when different design teams of subcontractors are involved. Clearly it follows a top-down approach.
- In contrast, the *failure mode, effects, and criticality analysis* (FMECA) (MILSTD-1629) follows a bottom-up approach. It considers each mode of failure of every component of a system to ascertain the effects on system operation and defines a *failure mode criticality number.*
- The *zonal safety analysis* (ZSA), rather than looking at an aircraft from a functional point of view, looks at the components' location. The ZSA checks installation rules and checks the effects of events originating within the zone, in other zones, or on the outside.

Software defies the above calculations and methods. However, information can be drawn from RTCA/DO-178B, which deals with *software considerations* in airborne systems and equipment. *Environmental conditions* for airborne equipment are presented in RTCA/DO-160D.

Mass

Mass estimation of aircraft systems is part of the mass (or weight) estimation of the whole aircraft.

The mass of all the aircraft systems m_{SYS} amounts to 23–40% of the aircraft's empty mass m_{OE}, where m_{OE} is the mass related to the operational empty weight (OEW). The figure 23% is true in case of a modern long-range airliner, whereas 40% is about right for a smaller aircraft such as business jet. Hence, for civil jet transport we may write

$$\frac{m_{\mathrm{SYS}}}{m_{\mathrm{OE}}} \approx 0.23-0.4$$

On average this ratio comes to ⅓, as stated above. Taking into account the ratio of the aircraft's empty mass m_{OE} and the maximum takeoff mass m_{MTO}, the mass related to the maximum takeoff weight (MTOW).

$$\frac{m_{\mathrm{SYS}}}{m_{\mathrm{MTO}}} \approx 0.11-0.23$$

Figure 2.1 shows the mass of aircraft systems of selected civil jet aircraft as a function of their maximum takeoff mass. We follow a *top-down approach* and fit a curve to these data to obtain

$$m_{\mathrm{SYS}} = 0.92\, m_{\mathrm{MTO}}^{0.85} \qquad \text{for } m_{\mathrm{SYS}} \text{ and } m_{\mathrm{MTO}} \text{ in kg}$$

This function is shown in Figure 2.1. The average relative mass of the individual systems of civil jet aircraft is given in Table 2.4.

Some aircraft systems, like the landing gear system (ATA 32) and the equipment and furnishings (ATA 25), account for a large percentage of the total aircraft system mass. The avionic system relative mass is 6% on average, but this figure depends on aircraft size because the amount of avionics needed in jet aircraft tends to be nearly constant. For this reason, the relative mass of avionic systems of business aircraft may be as high as 14% and as low as 5% in case of a large civil transport. As can be seen in Table 2.4, a number of systems are of minor importance for aircraft system mass predictions.

Alternatively, it is also possible to follow a *bottom-up approach*. This statistical technique uses system parameters to predict the mass of the system. Equations are given in Raymer (1992), Roskam (1989), and Torenbeek (1988). In addition, the knowledge gathered in papers from the Society of Allied Weight Engineers should be tapped (see SAWE 2002).

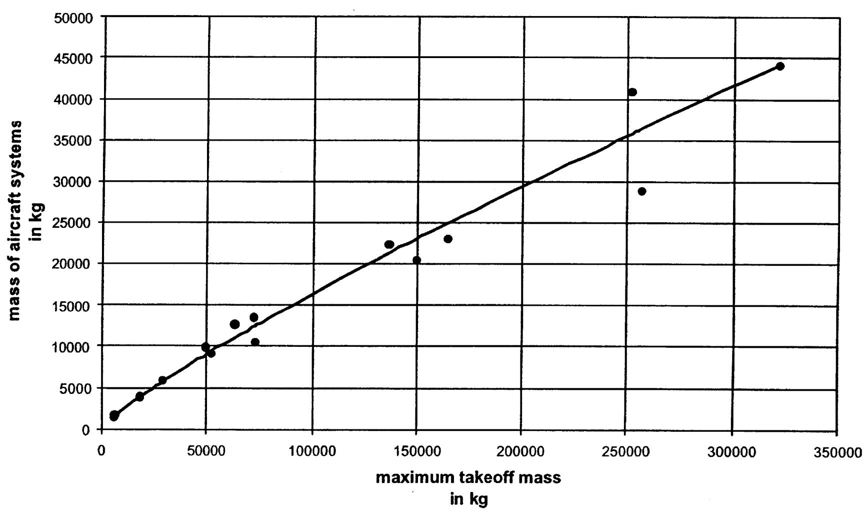

FIGURE 2.1 Mass of aircraft systems of selected civil jet aircraft plotted against their maximum takeoff mass.

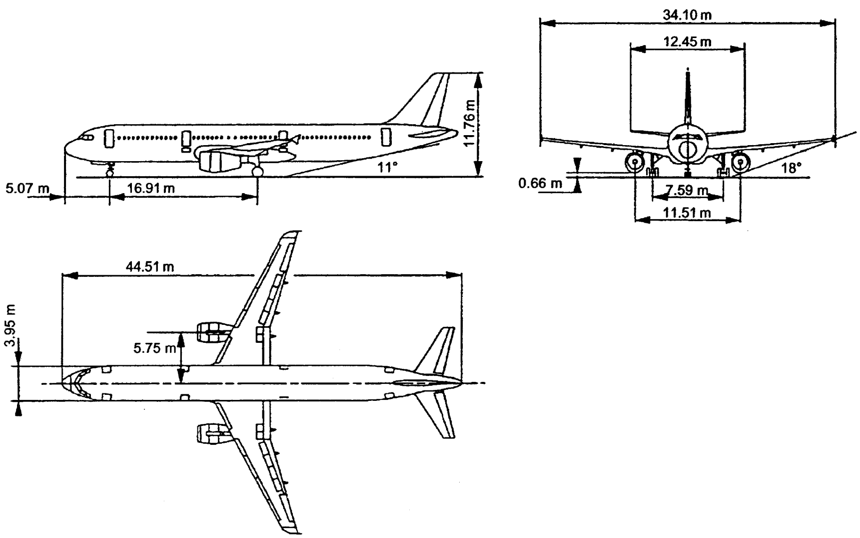

Figure 2.2 The Airbus A321 is used throughout this section to provide aircraft system examples. One hundred eighty-six passengers in two-class layout, MTOW: 83,000 kg, M_{MO} = 0.82, maximum FL 390.

Identifier	Name of system	Average relative mass of system
21	Air conditioning	6%
22	Auto flight	1%
23	Communications	2%
24	Electrical power	10%
25	Equipment/furnishings	24%
26	Fire protection	1%
27	Flight controls	8%
28	Fuel	3%
29	Hydraulic power	7%
30	Ice and rain protection	<1%
31	Indicating/recording systems	<1%
32	Landing gear	27%
33	Lights	2%
34	Navigation	3%
35	Oxygen	1%
36	Pneumatic	2%
38	Water/waste	1%
49	Airborne auxiliary power	2%

Table 2.4 Average Relative Mass of Aircraft Systems of Civil Jets

Statistics of aircraft system mass have to take as many aircraft into account as possible in order to broaden the statistical base. This, however, is really possible only if mass data are based on comparable and detailed mass breakdowns. Unfortunately, there are many quite different breakdowns in use, and it is found that system boundaries overlap from one method to another or are not well defined in the first place. So in the present situation it is very difficult to use and compare mass data and mass equations based on one of these breakdowns in another setting. This situation adds to the difficulties that exist with statistical methods anyhow and explains why statistical mass equations for systems or subsystems do not provide particularly reliable data.

Boeing has used a *breakdown format* called Weight Research Data 1 (WRD1). In the literature, breakdowns very similar to WRD1 can be found. Airbus uses so-called Weight Chapters. Another approach is given with MIL-STD-1374. Above we have used a mass breakdown according to the ATA 100 chapter numbering. ATA 100 also includes a widely accepted mass breakdown for weight and balance manuals. This breakdown, however, provides only as much detail as needed in aircraft operation but not enough detail for aircraft system design.

Note that aircraft system *mass predictions* deteriorate in *accuracy* when the level of detail is increased. For its old class I weight prediction method, Boeing estimates the prediction of single systems to be off by as much as ±90%. In contrast, the resultant mass of all systems combined is claimed to be off by not more than ±16% (Boeing 1968). This is because many inaccuracies combined fortunately cancel out to a certain extent.

Detailed system mass predictions are also necessary for *center of gravity* (CG) *calculation* for the aircraft. The main landing gear accounts for about 87% and the nose landing gear for the remaining 13% of the complete landing gear mass. With known positions of nose and main landing gear, this information can be fed into the CG calculation of the aircraft. The CG of the other systems can roughly be assumed at a point 40–50% of the fuselage length aft of the aircraft nose.

Practical mass predictions will look like this: In the early design stage, statistical methods are used. The aircraft manufacturer can also use the information contained in the mass database of older aircraft for the new design. In a later design stage a subcontractor will offer a system or an item of equipment. The subcontractor probably has quite a good idea what the item's mass will be from a comparison with similar items already built. If the required size of equipment is different from an older one, a mass estimate may be obtained from scaling. In the final development stage, mass accounting can be based on the actual mass of components that are already delivered to the manufacturer.

There is another virtue in mass predictions: the system mass has been used for rough *cost calculations.* This is possible when, from statistics, costs per unit mass are known and costs are assumed to be proportional with mass. Evidently, the concept of calculating costs from mass fails if expensive mass reduction programs are being applied. The concept also fails if highly sophisticated technologies are applied to reduce mass that are not considered in the established cost per unit mass.

Power

Gliders use the energy of up-currents, while solar-powered vehicles use the energy from the sun. Human-powered flight has also been demonstrated. Propulsive power for any other "down to earth" flying depends on fuel. This fuel is used in the aircraft main engines. *Secondary power* systems (hydraulic power, electrical power, pneumatic power) in turn draw on engine power to supply their client systems with *nonpropulsive power* in all those cases where functions are not directly actuated by the pilot's muscles. This is the simple picture of the aircraft power management. However, there is more to it, due to safety requirements and the need for autonomous operation of the aircraft on the ground with engines shut down.

Various secondary power sources are available in the air and on the ground. Secondary power loads may be grouped into two major categories. Power conversion transforms secondary power from one form into another.

An *auxiliary power unit* (APU) (see above) is used to produce power from fuel independent of the main engines. An APU is a gas turbine engine. Most often it produces electrical power and pneumatic power. A *ram air turbine* (RAT) (see Subsection 2.8) is used to produce hydraulic or electrical power from the kinetic energy of the air passing by the aircraft. This is possible even without fuel and without the main engines running—at least as long as the aircraft soars down consuming its potential energy. Except for the pilot's own energy, the *aircraft batteries* are the last and very limited source of energy on board.

Ground power may be available on the apron or in the hangar. The aircraft may be supplied directly with electricity, high-pressure hydraulic fluid, pressurized air, and/or air conditioned air. Human power could work a hand pump in the hydraulic system. If only electrical ground power is available, the aircraft depends on its secondary power conversion capabilities to activate the hydraulic and pneumatic system. Without ground equipment and with engines shut down, the aircraft may operate autonomously if it is equipped with an auxiliary power unit (APU).

First of all, *secondary power loads* may be grouped into:

- Technical loads consumed by equipment required to operate the aircraft safely
- Commercial loads consumed by equipment required to increase passenger comfort and satisfaction, given the airline's need to provide these services

Power conversion among different[3] secondary power systems is used to increase overall system reliability. If we consider electrical power, hydraulic power, and pneumatics:

- Six different unidirectional conversions are possible. Examples are:
  - Electrical to hydraulic power conversion: electric motor-driven pump
  - Pneumatic to hydraulic power conversion: air turbine motor-driven pump
  - Hydraulic to electrical power conversion: hydraulic motor-driven generator
- Three different bidirectional conversions are possibilities that allow a two-way power conversion among two different secondary power systems within one conversion unit.

For many years hydraulic, pneumatic, and electrical power supply in commercial aircraft had been sufficient to meet the demands from technical and commercial loads. System design emphasized reliable, lightweight solutions. From fuel input to system output, very low overall efficiencies were accepted in exchange.

In recent years it has been observed that aircraft face increasing technical loads. Also, market trends together with increasing flight durations have resulted in higher commercial loads, caused, for example, by today's standards in in-flight entertainment. Possibilities for power off-takes do not increase proportionally with aircraft size. Large modern civil aircraft are therefore likely to face limitations of cost effectiveness, geometry, or weight with present-day technologies in an attempt to meet these new power load levels. The aerospace industry has identified a potential deadlock, where power needs will exceed the maximum available power supply.

In the future a move toward electrical power as a single source to meet secondary power demands is expected to be a solution to the problem. The last aircraft generation brought steering by wire. The next generation of aircraft might bring power by wire.

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[3]Power conversion is even applied within one type of secondary power system: the hydraulic system. Transport category aircraft apply several independent hydraulic systems. Among pairs of these hydraulic systems unidirectional or bidirectional hydraulic power transfer without the interchange of hydraulic fluid can be desirable. For this purpose, power transfer units (PTU) (ARP 1280) are used. They are built by coupling a hydraulic motor and a hydraulic pump via a connecting shaft.

Costs and Trade-Off Studies

Trade-off studies play an important roll in aircraft system design. Trade-off studies try to find the best among several system design proposals. Safety aspects allow no compromise because certification regulations have to be closely followed. Also, performance aspects leave little room because usually only as much performance as necessary to do the job will be allowed for. More powerful aircraft systems will unnecessarily produce costs that add to the overall costs of the aircraft. Clearly, costs need to be reduced as much as possible to come up with a viable product. Therefore, it is the costs aspect that is usually decisive in trade-off studies of which system design will get on board the aircraft.

At the aircraft system level, evaluations are done in the early design stage by looking separately at various aspects:

- Mass
- Maintainability
- Reliability
- System price
- Other specific criteria depending on the aircraft system in question

Based on these separate evaluations, the simplest way to come up with one single figure of merit for a proposal is to define subjectively a *weighted sum* of the results based on the individual criteria.

In contrast to the above approach, at the aircraft level an evaluation is traditionally based primarily on one single figure: the direct operating costs (DOC). DOCs take account of criteria such as mass, maintainability, and aircraft price, but combine these separate parameters unambiguously by calculating their economical implications. Subjective manipulations of the results are largely avoided in this way.

Unfortunately, aircraft DOC methods cannot be taken as is for applying this advantage to an aircraft system evaluation. In contrast to aircraft DOC methods, a DOC method on the systems level must incorporate many system-specific parameters. Therefore, a *DOC method for aircraft systems* called $\mathrm{DOC_{SYS}}$ has been developed (Scholz 1998) which follows the principles of aircraft DOC methods as closely as possible while taking aircraft system peculiarities into account as much as necessary.

$$C_{\mathrm{DOC,SYS}} = C_{\mathrm{DEP}} + C_F + C_M + C_{\mathrm{DEL}} + C_{\mathrm{SH}}$$

where C_{DEP} = depreciation of the system (a function of system price)
C_F = fuel costs caused by the system
C_M = direct maintenance costs caused by the system
C_{DEL} = delay and cancellation costs caused by the system
C_{SH} = capital costs caused by necessary system spare parts on stock (spare holding)

The fuel costs, C_F, are due to:

- Transportation of the system's mass (fixed or variable during flight) (taking into account the lift-to-drag ratio of the aircraft and the specific fuel consumption of the engines)
- Power off-takes from the engines (by electrical generators or hydraulic pumps)
- Bleed air off-takes (for the pneumatic system)
- Ram air off-takes (e.g., for the air conditioning system)

- Additional drag caused by the presents of aircraft systems, subsystems, or single parts (e.g., due to drain masts)

In contrast to Scholz (1998), who combines various system aspects to U.S. dollars, Shustrov (1998) combines system mass effects and effects related to the system's energy consumption to a quantity called *starting mass*.

Proprietary methods for the evaluation of aircraft systems are in use at aircraft manufacturers and subcontractors.

2.2 Air Conditioning (ATA 21)

Air conditioning as defined by ATA 100:

> Those units and components which furnish a means of pressurizing, heating, cooling, moisture controlling, filtering and treating the air used to ventilate the areas of the fuselage within the pressure seals. Includes cabin supercharger, equipment cooling, heater, heater fuel system, expansion turbine, valves, scoops, ducts, etc.

Fundamentals

Impact of Atmospheric Parameters

In the troposphere, the air temperature decreases with increasing altitude. In the stratosphere above 11,000 m (36,089 ft), the air temperature is at constant –56.5 °C. The air pressure also decreases with altitude. Although oxygen amounts to approximately 21% independent of altitude, the partial pressure[4] of oxygen drops with increasing altitude. Our body is used to a partial oxygen pressure of about 0.21 times sea level pressure. If we want to survive at high altitudes, either (a) the oxygen fraction has to be increased (using an oxygen system), or (b) the total pressure has to be maintained close to sea level pressure (using a pressurization system). For civil aircraft generally option (b) is applied; flights in nonpressurized cabins[5] without supplemental oxygen are limited to an altitude of 10,000 ft. Military aircraft use a combination of (a) and (b); cabin altitude[6] does not exceed about 20,000 ft.

Purpose of Air Conditioning Systems

The purpose of the air conditioning system is to make the interior environment of the aircraft comfortable for human beings. Depending on the type of aircraft and altitude of operation, this may involve only *ventilation* of the cabin by supplying a flow of fresh air using air vents. If the temperature must be adjusted, some method of *heating* or *cooling* is required. At high altitudes the aircraft can fly above most of the weather conditions that contain turbulence and make flight uncomfortable. Additionally, the fuel efficiency of the aircraft is increased. *Pressurization* is necessary if the aircraft is operated at these high altitudes. In some parts of the world the relative humidity[7] is quite high. Water extractors are therefore used for *dehumidification* of the cabin air. This is necessary to

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[4]Partial pressure: "The pressure exerted by one gas in a mixture of gases; equal to the fraction … of one gas times the total pressure" (AIR 171).

[5]Nonpressurized cabin: "An airplane cabin that is not designed … for pressurizing and which will, therefore, have a cabin pressure equal to that of the surrounding atmosphere" (SAE 1998).

[6]Cabin altitude: "The standard altitude at which atmospheric pressure is equal to the cabin pressure" (SAE 1998).

[7]Relative humidity: "The ratio, expressed as percentage, of the amount of water vapor … actually present in the air, to the amount of water vapor that would be present if the air were saturated with respect to water at the same temperature and pressure" (SAE 1998).