Doc 7488/3

MANUAL OF THE ICAO STANDARD ATMOSPHERE

extended to 80 kilometres (262 500 feet)

MANUEL DE L’ATMOSPHÈRE TYPE OACI

élargie jusqu’à 80 kilomètres (262 500 pieds)

MANUAL DE LA ATMÓSFERA TIPO DE LA OACI

ampliada hasta 80 kilómetros (262 500 pies)

РУКОВОДСТВО ПО СТАНДАРТНОЙ АТМОСФЕРЕ ИКАО

с верхней границей, поднятой до 80 километров (262 500 футов)

THIRD EDITION — TROISIÈME ÉDITION
TERCERA EDICIÓN — ТРЕТЬЕ ИЗДАНИЕ

1993

INTERNATIONAL CIVIL AVIATION ORGANIZATION
ORGANISATION DE L’AVIATION CIVILE INTERNATIONALE
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МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ГРАЖДАНСКОЙ АВИАЦИИ

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FOREWORD

As the result of recommendations made by the Airworthiness, the Operations and Meteorological Divisions, the ICAO Council at a meeting on 23 June 1950 agreed that a joint sub-commission of the Commission for Aeronautical Meteorology and the Aerological Commission of the International Meteorological Organization be established. Its mandate was to discuss with representatives of ICAO the establishment of a detailed specification of and the collection of data for the ICAO standard atmosphere defined in general terms in Part I of Annex 8 to the Convention on International Civil Aviation.

A working group consisting of the above-mentioned representatives met in July/August 1950 in Montreal and drafted a proposal for a detailed specification of the ICAO standard atmosphere. This proposal was included in Doc 7041 and at the beginning of 1951 was circulated to all Contracting States for comment.

On 7 November 1952 the Council approved the specification as detailed in Doc 7041 and directed the Secretary General to publish the specification and its associated tables and figures in the form of a technical manual.

All assumptions and basic data used in that manual were those adopted by the Council of ICAO. The mechanical work of calculating and checking the detailed tables and figures of the ICAO standard atmosphere was carried out by the United States National Advisory Committee for Aeronautics in co-operation with the Directorate General of Civil Aviation, Italy. By courtesy of these two governments, their work was made available for inclusion in that manual, which was published as ICAO Document 7488 (May 1954).

Even before publication of Doc 7488, it had become apparent that the ICAO standard atmosphere needed to be extended above the previously adopted limit of 20 km. In 1953 a Committee was created in the United States sponsored jointly by the Geophysics Research Directorate of the Air Force Cambridge Research Center and the United States Weather Bureau. During the same year representatives of 24 United States scientific and engineering organizations — both governmental and private — attended a meeting, to which ICAO sent an observer. The Committee decided to appoint a "Working Group on Extension to the Standard Atmosphere" to reconsider the temperature-altitude profile and to recommend basic values and parameters. The working group continued its activities during the years 1953 to 1956 and its recommendations, including a definition of the temperature-altitude profile up to 32 km, were adopted with modifications by the parent committee in 1956. In 1958 a report entitled "U.S. Extension to the ICAO Standard Atmosphere Tables and Data to 300 Standard Geopotential Kilometers" was issued in Washington, D.C. In 1959 the report was sent to the Secretary General of ICAO by the Representative of the United States on the Council of ICAO proposing international adoption of the 20 to 32 km portion of the report; however, the proposal was subsequently withdrawn pending the availability of revised data.

In 1962 detailed proposals for changes in certain constants associated with the ICAO standard atmosphere and for the extension of the standard atmosphere were submitted by the United States, together with the document "U.S. Standard Atmosphere — ICAO Standard Atmosphere to 20 km, Proposed ICAO extension to 32 km, Tables and Data to 700 km." This revised U.S. proposal was circulated for comment to all Contracting States, the International Air Transport Association, the International Federation of Air Line Pilots' Associations and the World Meteorological Organization.

On 12 November 1963 the Council approved the revised detailed specification of the ICAO standard atmosphere, and directed the Secretary General to re-issue the Tables of ICAO Standard Atmosphere, incorporating the revision and extension prepared by the United States. In accordance with the foregoing directive, the second edition of the manual was published in 1964.

On 23 March 1979 the Council approved the alignment of the system of units of measurement used in aviation (as specified in Annex 5) with the international system (SI). In line with the Council's wish that all ICAO documents comply with Annex 5 in respect of the units used, arrangements were made to revise the Manual of the ICAO Standard Atmosphere. Due to the fact that the second edition of the manual contained a complex mixture of SI units and non-SI units, the data in some of the tables had to be recalculated.

In addition to the question of the alignment of the units with Annex 5, two States (the Union of Soviet Socialist Republics and the United States), noting the possibility of the development in the foreseeable future of aircraft capable of flying at very high altitudes, requested that the ICAO standard atmosphere be extended from the existing upper limit of 32 km to 80 km, which would correspond approximately to the height of the mesopause. The proposal to extend the upper limit of the standard atmosphere was circulated to all Contracting States for comment, and following consideration of States' replies, the Council, on 22 March 1988, adopted Amendment No.95 to Annex 8, which included the extension of the standard atmosphere to 80 km. As the revision of the manual to align it with Annex 5 already entailed recalculation of some of the tables, it was considered that this would also be an appropriate time to extend the atmosphere's upper limit.

The recalculation of the data in certain of the existing tables and the extension of the data in all tables from 32 km to 80 km necessarily required the use of sophisticated computer facilities in order to retain the existing level of accuracy of the data. At the time this task was started, the International Organization for Standardization (ISO) had recently published a standard atmosphere up to 80 km based upon the ICAO parameters defined in Annex 8. In an attempt to align the ICAO and ISO standard atmospheres, ISO was approached for assistance in providing the data needed for the revision and extension of the ICAO standard atmosphere. The competent ISO working body, Sub-committee ISO/TC-20/SC-6-Standard Atmosphere, in a meeting held in Moscow in October 1985, decided unanimously to provide assistance in recalculating the tables required for the alignment of Doc 7488 with Annex 5 and in extending its upper limit in accordance with Annex 8.

The method used for calculating the parameters and the necessary software were developed in the Central Aero-Hydrodynamic Institute (TSAGI), Union of Soviet Socialist Republics. The actual calculations were also carried out by the Union of Soviet Socialist Republics on behalf of the ISO committee, in accordance with the ICAO requirements and the ISO/TC-20/SC-6 plans. The result of the ISO work is being issued in parallel as Addendum 2 to International Standard ISO 2533: 1975, Standard Atmosphere.

This manual is intended to facilitate the uniform application of the ICAO standard atmosphere defined in Annex 8 and to provide users of the standard atmosphere with convenient sets of data that are accurate enough for practical applications, and that are based on internationally agreed physical constants and conversion factors. In view of the fact that the data tables published for the ICAO and ISO Standard Atmospheres are identical, any future amendments will be the subject of co-ordination between the two organizations.

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INTRODUCTION

General Note.— The decimal notation used in this manual conforms to ICAO practice. The ISO practice is to use a decimal point (.) in imperial measurements and a comma (,) in metric measurements.

1. SCOPE AND FIELD OF APPLICATION

This international standard specifies the characteristics of an ICAO standard atmosphere. It is intended for use in calculations in the design of aircraft, in presenting test results of aircraft and their components under identical conditions, and to facilitate standardization in the development and calibration of instruments. Its use is also recommended in the processing of data from geophysical and meteorological observations.

2. BASIC PRINCIPLES AND CALCULATION FORMULAE

2.1 Primary constants and characteristics

The tables of the ICAO standard atmosphere have been calculated assuming the air to be a perfect gas free from moisture and dust and based on conventional initial values of temperature, pressure and density of the air for mean sea level. The following constants and characteristics are used for calculations and their numerical values are given in Table A:

g_0 — standard acceleration due to gravity. It conforms with latitude $\varphi = 45°32'33''$ using Lambert's equation of the acceleration due to gravity as a function of latitude φ (see reference 1):

$$g_\varphi = 9.806\,16(1 - 0.002\,637\,3\cos 2\varphi + 0.000\,005\,9\cos^2 2\varphi)$$

M_0 — sea level mean molar mass, as obtained from the perfect gas law (equation (2)) when introducing the primary constants P_0, ρ_0, T_0, R^* (see Table A);

N_A — Avogadro constant, based on the value of the nuclide ^{12}C, atomic mass = 12.000, as adopted in 1961 by the Conference of the International Union of Pure and Applied Chemistry as the basic atomic mass unity;

P_0 — sea level atmospheric pressure;

R^* — universal gas constant;

$R = R^*/M_0$ — specific gas constant;

S and β_s — Sutherland's empirical constants in the equation for dynamic viscosity;

T_i — temperature of the ice point at mean sea level;

T_0 — sea level temperature;

t_i — Celsius temperature of the ice point at mean sea level;

t_0 — Celsius sea level temperature;

$\kappa = c_p/c_v$ — adiabatic index, the ratio of the specific heat of air at constant pressure to its specific heat at constant volume;

ρ_0 — sea level atmospheric density;

σ — effective collision diameter of an air molecule; taken as constant with altitude.

2.2 The hydrostatic equation and the perfect gas law

Being static with respect to the earth, the atmosphere is subject to gravity. The conditions of air static equilibrium are determined by the hydrostatic equation which relates air pressure p, density ρ, acceleration due to gravity g and altitude h as follows:

$$-dp = \rho g dh \qquad (1)$$

Table A. Primary constants and characteristics adopted for the calculation of the ICAO standard atmosphere

Symbol	Value	Unit of measurement
g_0	9.806 65	m/s^2
M_0 (see Note)	28.964 420	kg/kmol
N_A	602.257×10^{24}	$kmol^{-1}$
P_0	101.325×10^3	Pa
	1 013.250	hPa
R^*	8 314.32	J/(K · kmol) *or* $kg \cdot m^2/(s^2 \cdot K \cdot kmol)$
R (see Note)	287.052 87	J/(K · kg) *or* $m^2/(K \cdot s^2)$
S	110.4	K
T_i	273.15	K
T_0	288.15	K
t_i	0.00	°C
t_0	15.00	°C
β_s	1.458×10^{-6}	$kg/(m \cdot s \cdot K^{1/2})$
κ	1.4	dimensionless
ρ_0	1.225	kg/m^3
σ	0.365×10^{-9}	m

Note.— Not a primary constant per se; derived from primary constants.

The perfect gas law relates air pressure to density and temperature as follows:

$$p = \frac{\rho R^* T}{M_0} \qquad (2)$$

At the altitudes considered in this International Standard,

$$\frac{R^*}{M_0} = constant = R$$

then

$$p = \rho R T \qquad (3)$$

2.3 Geopotential and geometric altitudes; acceleration due to gravity

In considering pressure distribution in the atmosphere, it is convenient to introduce the gravity potential or geopotential Φ, which characterizes the potential energy of an air particle at a given point.

Any point with *x,y,z* coordinates may be characterized by a single value of gravity potential $\Phi(x,y,z)$ in it. The surface defined by the equation

$$\Phi(x, y, z) = constant$$

is of the same potential in all points and is called an isopotential or geopotential surface. When moving along an external normal from any point on the surface Φ_1, to the infinitely close point where the value of the potential is $\Phi_2 = \Phi_1 + d\Phi$, the work performed for shifting a unit mass from the first surface to the second one will be:

$$d\Phi = g(h)dh \qquad (4)$$

hence

$$\Phi = \int_0^h g(h)dh \qquad (5)$$

By dividing the geopotential Φ by the standard acceleration due to gravity g_0, one obtains the value of a length dimension which, symbolized as H, will be:

$$H = \frac{\Phi}{g_0} = \frac{1}{g_0}\int_0^h g(h)dh \qquad (6)$$

Expressed in metres, the value H is numerically equal to the geopotential altitude, which in meteorology is measured in so-called standard geopotential metres; hence, this value will be called geopotential altitude. The mean sea level is taken as a reference for readings for both geopotential and geometrical altitudes.

Note.— The standard geopotential metre (m′), which is equal to 9.806 65 m^2/s^2, has been adopted by the World Meteorological Organization (see Technical Regulations, *WMO, No. 49, Volume 1, ed. 1971 — Appendix C) and from 1 July 1972 replaces the geopotential metre formerly in use. Its value was 1 gpm = 9.8 m^2/s^2.*

From equation (6) it can be seen that, in order to relate geopotential and geometric altitudes, it is necessary first to find a relationship between acceleration due to gravity g and geometric altitude h.

It is known that gravity is a vectorial summation of the gravitational attraction and the centrifugal force induced by the earth's rotation; it is therefore a complex function of a latitude and a radial distance from the earth's centre and the expression for acceleration due to gravity is generally awkward and unpractical for use. However, the acceleration g may be obtained with sufficient accuracy for the purpose of this standard atmosphere by formally neglecting centrifugal acceleration and using only Newton's gravitation law. In this case:

$$g = g_0\left(\frac{r}{r + h}\right)^2 \qquad (7)$$

where r = 6 356 766 m is the nominal earth's radius (see reference 1), for which acceleration due to gravity and the vertical gradient of acceleration at mean sea level are very close to true values at the latitude 45°32′33″.

The values of g, as calculated using the simplified equation (7) with g_0 = 9.806 65 m/s^2 for the altitude of 60 000 m, do not differ by more than 0.001 per cent from the values calculated using the more accurate equation (6).

Integration of equation (6), substituting for g with its function from equation (7), gives the following relationship between geopotential and geometric altitudes:

$$H = \frac{rh}{r + h} \qquad (8)$$

$$h = \frac{rH}{r - H} \qquad (9)$$

2.4 Atmospheric composition and mean molar mass

The earth's atmosphere is a mixture of gas, water vapour and a certain quantity of aerosol. Under certain conditions, the quantities of water vapour, carbon dioxide and ozone, as well as other components which occur in insignificant amounts in the atmosphere, may vary. The water vapour undergoes the greatest variations. Its concentration at the earth's surface may reach 4 per cent under high temperature conditions; however, this decreases with altitude as the temperature decreases. Dry, clean air composition up to altitudes of 90 to 95 km remains practically constant and corresponds to that given in Table B.

The mean molar mass is determined from the perfect gas law (equation (2)) using the standard values of pressure P_0, density ρ_0 and temperature T_0 for mean sea level, as well as the universal gas constant R^*.

2.5 Physical characteristics of the atmosphere at mean sea level

For the calculation of the ICAO standard atmosphere, the mean sea level is defined as zero altitude for which the initial characteristics g_0, P_0, ρ_0 and T_0 given in Table A apply. The remaining characteristics have been calculated using the initial ones as a basis and are presented in Table C:

a_0 speed of sound;

H_{p0} pressure scale height;

Table B. Dry, clean air composition near sea level[1]

Gas		Content of volume %	Molar mass M kg/kmol
Nitrogen (N_2)		78.084	28.013 4
Oxygen (O_2)		20.947 6	31.998 8
Argon (Ar)		0.934	39.948
Carbon dioxide (CO_2)		0.031 4*	44.009 95
Neon (Ne)		1.818×10^{-3}	20.183
Helium (He)		524.0×10^{-6}	4.002 6
Krypton (Kr)		114.0×10^{-6}	83.80
Xenon (Xe)		8.7×10^{-6}	131.30
Hydrogen (H_2)		50.0×10^{-6}	2.015 94
Nitrogen monoxide (N_2O)		50.0×10^{-6}*	44.012 8
Methane (CH_4)		0.2×10^{-3}	16.043 03
Ozone (O_3)	in summer	up to 7.0×10^{-6}*	47.998 2
	in winter	up to 2.0×10^{-6}*	47.998 2
Sulphur dioxide (SO_2)		up to 0.1×10^{-3}*	64.062 8
Nitrogen dioxide (NO_2)		up to 2.0×10^{-6}*	46.005 5
Iodine (I_2)		up to 1.0×10^{-6}*	253.808 8
Air		100	28.964 420**

* The content of the gas may undergo significant variations from time to time or from place to place.
** This value is obtained from the perfect gas law (equation (2)).

1. *U.S. Committee on Extension to the Standard Atmosphere: U.S. Standard Atmosphere,* 1962. U.S. Government Printing Office. Washington, D.C. 1963.

l_0 mean free path;

n_0 number density;

$\overline{v}_0$ mean particle speed;

γ_0 specific weight;

υ_0 kinematic viscosity;

λ_0 thermal conductivity;

μ_0 dynamic viscosity;

ω_0 collision frequency.

2.6 Temperature and vertical temperature gradient

Temperature of the ice point under a pressure of 1 013.25 hPa is taken as T_i = 273.15 K. Temperature T (in Kelvins, K) is:

$$T = T_i + t \qquad (10)$$

where t is the Celsius temperature.

According to the temperature variations with altitude, the atmosphere is divided into several layers. The transitional zones between these layers are called tropopause, stratopause and mesopause respectively. For calculating a standard atmosphere, the temperature of each layer is taken as a linear function of geopotential altitude, so that

$$T = T_b + \beta(H - H_b) \qquad (11)$$

where T_b and H_b are respectively the temperature and the geopotential altitude of the lower limit of the layer concerned and β is the vertical temperature gradient, dT/dH.

The values of temperature and its vertical gradients adopted for the ICAO standard atmosphere are given in Table D.

2.7 Pressure

Assuming a linear variation of the temperature with geopotential altitude, the simultaneous solution of the hydrostatic equation (equation (1)) and the perfect gas law (equation (2)) yields the following expression for pressure:

Table C. Physical characteristics of the atmosphere at mean sea level

Symbol	Value	Unit of measurement
a_0	340.294	m/s
H_{p_0}	8 434.5	m
l_0	66.328×10^{-9}	m
n_0	25.471×10^{24}	m^{-3}
$\overline{v}_0$	458.94	m/s
γ_0	12.013	N/m^3
υ_0	14.607×10^{-6}	m^2/s
λ_0	25.343×10^{-3}	W/(m · K)
μ_0	17.894×10^{-6}	Pa · s
ω_0	$6.919\,3 \times 10^{9}$	s^{-1}